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THE ORIGIN OF BANDED HEMATITE ORES IN INDIA.[1]

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INTRODUCTION.

DEPOSITS of iron-ores occur in many parts of India, but the more important from the point of view of size and quality are in Singhbhum district and the adjacent Orissa States of Keonjhar, Bonai and Mayurbhanj, and in Bastar State. The minimum reserves of ore, containing over 60 percent Fe, are about 3,000 million tons in Singhbhum and adjacent Orissa States, and 610 million tons in Bastar. The actual quantities in the Orissa States are likely to be many times the amounts quoted. The Singhbhum and adjacent deposits have been described in recent years by

[1] Published with the approval of the Director, Geol. Surv. of India.

Jones,[2] Percival[3] and Dunn,[4] and Crookshank[5] has provided a brief account of the Bastar deposits.

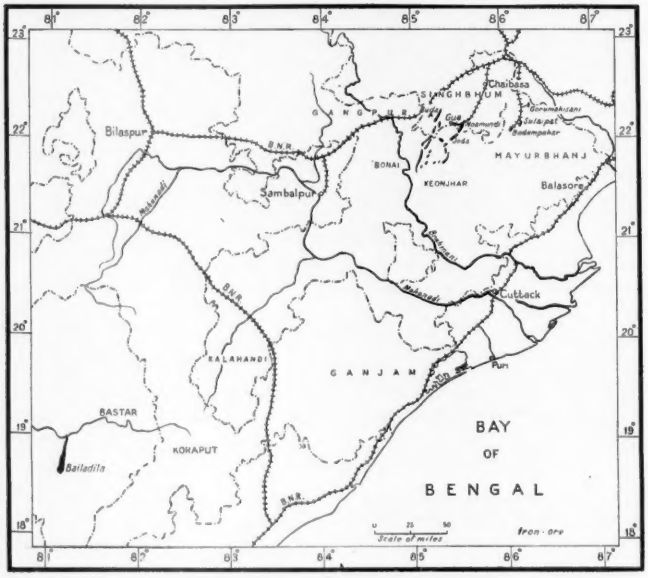

FIG. 1. Iron-ore localities, Eastern India.

Jones was concerned with mapping in South Singhbhum and Keonjhar. The writer has been responsible for mapping in North and East Singhbhum and Mayurbhanj, but recently has

[2] Jones, H. C.: The iron-ore deposits of Bihar and Orissa. Mem. Geol. Surv. India, LXIII (2), 1934.

[3] Percival, F. G.: The iron-ores of Noamundi. Trans. Min. Geol. Inst. India, XXVI (3 and 4), 1931.

[4] Dunn, J. A.: The geology of North Singhbhum including parts of Ranchi and Manbhum districts. Mem. Geol. Surv. India, LIV, 1929. The origin of iron-ores in Singhbhum, India. ECON. GEOL., XXX: 643–654, 1935. The mineral deposits of Eastern Singhbhum and surrounding areas. Mem. Geol. Surv. India, LXIX (1), 1937.

[5] Crookshank, H.: The iron-ores of the Bailadila Range, Bastar State. Trans. Min. Geol. Met. Inst. India, 34 (3): 253–281, 1938.

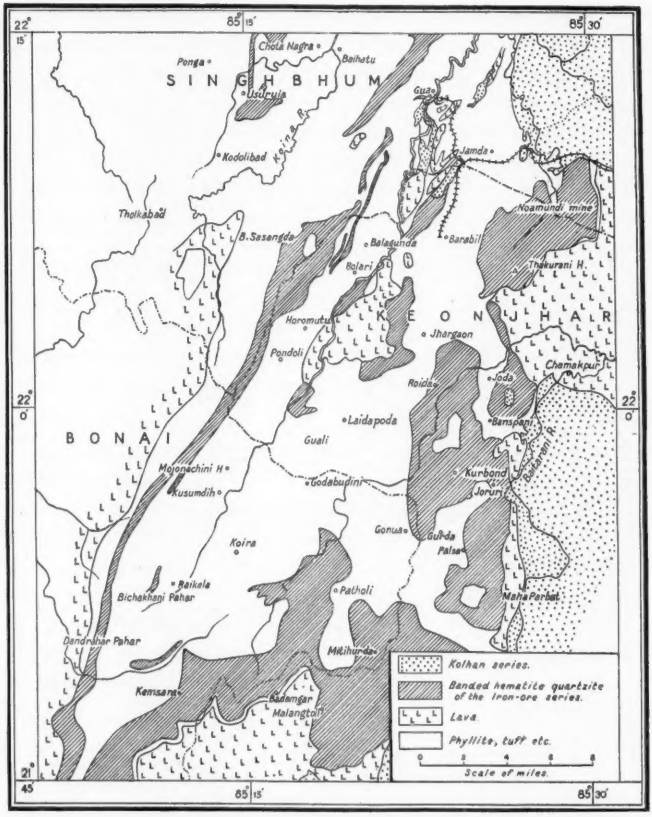

FIG. 2. Map showing the distribution of the banded hematite quartzites in South Singhbhum and states of Bonai and Keonjhar.

had occasion to examine in greater detail the main area of the iron-ore deposits in South Singhbhum, previously mapped by Jones, and has found it necessary to revise the latter's stratigraphical conclusions.[6] There are several important points of

[6] Dunn, J. A.: The stratigraphy of South Singhbhum. Mem. Geol. Surv. India, LXIII (3), 1940.

difference, and others of similarity, in the geology and ores of the two areas: South Singhbhum and Keonjhar, and North and East Singhbhum and Mayurbhanj. It is proposed, here, to summarize the recently revised stratigraphy and to outline the view of the origin of these ores which the writer has formed after nearly twenty years acquaintance with them.

STRATIGRAPHY.

North and East Singhbhum.—Accounts of the Iron-ore Series in North [7] and East Singhbhum [8] have already appeared, and a more detailed description of the latter area is now in the press.[9] This part of Singhbhum is traversed in an east-west direction by a shear zone, on either side of which the rocks are grouped as follows:

North of the shear zone.	*South of the shear zone.*
Dalma lava.	Dhanjori group: Lava.
(overlap).	Dhanjori group: Sandstone-conglomerate.
	(unconformity).
Iron-ore stage: Phyllites.	Iron-ore stage: Phyllites.
Iron-ore stage: Quartzites, often ferruginous (impersistent).	Iron-ore stage: Banded quartzites, including banded hematite-quartzites (impersistent).
Iron-ore stage: Phyllites and tuffs, basic intrusives.	Iron-ore stage: Phyllites and tuffs, basic intrusives.
Chaibasa stage: Mica-schists, hornblende-schists and quartz-granulites.	

[7] Dunn, J. A.: The geology of Northern Singhbhum including parts of Ranchi and Manbhum districts. Mem. Geol. Surv. India, LIV, 1929.

[8] Dunn, J. A.: The mineral deposits of Eastern Singhbhum and surrounding areas. Mem. Geol. Surv. India, LXIX (1), 1937.

[9] Dunn, J. A., and Dey, A. K.: The geology and petrology of Eastern Singhbhum and surrounding areas. Mem. Geol. Surv. India, LXIX (2), *in press.*

The iron-ores are generally associated with the banded hematite-quartzite of the Iron-ore stage. This stage consists of highly chloritic phyllites, hematite phyllites, carbon and sericite phyllites, coarse and fine tuffs, banded cherty quartzites and sandstone quartzites (including rare conglomerates), and basic igneous rocks. The phyllites show all grades of metamorphism to mica-schists with the common development of ottrelite, staurolite, andalusite and kyanite. The banded cherty quartzites, in which the silica is commonly granular due to recrystallization, include banded hematite-quartzite, banded chlorite-quartzite, banded carbon-quartzite and banded sericite-quartzite, all of which it has been shown [10] are the silicified product of material now represented by the phyllites, which were apparently partly of tuff origin. The banding is determined by whether the original material was ferruginous, chloritic, carbonaceous or sericitic. Some of the coarser tuff breccias have also been silicified to cherts and the lavas have been silicified in places—a rare example of a banded hematite-quartzite derived by local silicification of a sheared basic igneous rock has even been observed.

In places, immediately at the unconformity below the Dhanjori conglomerate to the south of the shear zone, the chloritic phyllites are oxidized to hematite-phyllites that in many places are rich in iron. This oxidation was apparently sub-aerial and immediately preceded deposition of the conglomerate.

South Singhbhum.—The term Iron-ore Series was first introduced by Jones during the course of his mapping in South Singhbhum and Keonjhar State, and was applied to a group of rocks covering a large area. Recently, however, part of the Series in South Singhbhum has been found to belong to a much younger group, termed by the writer the Kolhan Series.[11] The unconformity at the base of the latter is clearly exposed in many sections, in streams, quarries, railway- and road-cuttings. The basal bed of the Kolhan Series consists of a sandstone-con-

[10] Dunn, J. A.: Mem. Geol. Surv. India, LXIX (1), 202, 1937, and LXIX (2), *in press;* The origin of iron-ores in Singhbhum, India. Econ. Geol., XXX: 646–647, 1935.

[11] Records Geol. Surv. India, 74 (1): 27–28, 1939.

glomerate which, close to the deposits of iron-ore within the Iron-ore Series, grades to a high-grade iron-ore conglomerate. Above this sandstone-conglomerate lie impersistent limestones and a thick group of shales.

In South Singhbhum and Keonjhar State, the Iron-ore Series consists of lavas, tuffs, phyllites, cherts and banded hematite-quartzites; the iron-ores normally occur as enriched zones within the latter. The true sequence is uncertain. It is clear, however, that there is some overlap between the main group of lavas and banded hematite-quartzites.

The banded hematite-quartzites are folded into the form of a horseshoe, closed to the southwest and open to the northeast where the limbs of the fold are 8 miles apart. Dips are persistently to the northwest. If the structure is geosynclinal, then the north-west limb is overfolded, if geo-anticlinal the south-eastern limb is overfolded. Assuming the structure to be synclinal, then the following would be the general succession:

phyllites and tuffs
banded hematite-quartzite
phyllites and tuffs (impersistent)
lava.

This succession will be inverted if the structure is anticlinal.

It is commonly noted that, along its junction with the banded hematite-quartzite, the lava, commonly amygdaloidal, is much altered and replaced by hematite. Phyllitic tuffs forming a thin zone between the lavas and quartzites may be similarly replaced. Alteration and hematitization of the lavas immediately below the Kolhan unconformity also is commonly seen—such alteration of basic and acid lavas immediately below comparable unconformities has been noticed in the Pre-Cambrian of other parts of India, and is attributed to contemporaneous oxidation and surface concentration of iron-oxide under sub-aerial conditions.

ORIGIN OF THE BANDED HEMATITE-QUARTZITES.

General.—Deposits of hematite in Singhbhum have been formed more particularly by enrichment of the banded hematite-

quartzites, less commonly by replacement of phyllitic tuffs, and in a few places by replacement of lavas. The source of the iron has been within the rocks themselves. Apart from the mode of enrichment, the origin of the main ore-bodies is related to the origin of the banded hematite-quartzites.

The banded hematite-quartzite has been described by Jones, Percival and Dunn. The name is unfortunately cumbersome; the term banded jasper would have been suitable, providing the recrystallized nature of the quartz in many places is remembered. It is similar to the "calico rock" of South Africa and the itabirite of Brazil and to some of the taconite, jaspilite or banded jasper of Lake Superior. It consists of alternating bands of hematite, jasper and white cherty or granular quartz. In the field all gradations can be detected from fine-banded types to massive beds of jasper and white chert. Close folding is everywhere distinguishable in these banded quartzites; quite commonly the fine bands are so minutely puckered that it is difficult to appreciate how such minute folds could have been imparted to what is apparently a very competent rock. But, under pressure, the ferruginous laminæ would yield readily, the thin silica layers following suit.

The literature dealing with the origin of these banded hematite-quartzites in India and other countries, particularly in the United States, is extensive enough and is summarized elsewhere.[12] An overwhelming amount of evidence has been gathered in the Lake Superior region indicating that these rocks accumulated under submarine conditions as rhythmically banded ferruginous sediments, except perhaps in the Vermillion Range where the origin is possibly different. The ferruginous material was deposited as carbonate, as greenalite, or as oxide. The original source of the material has been widely discussed: some believe that the silica and ferrous minerals were derived from magmatic solutions poured over the sea bottom;[13] others believe that the iron and

[12] Dunn, J. A.: Mem. Geol. Surv. India, LXIX (1): 197–206, 1937.

[13] Van Hise, C. R., and Leith, C. K.: The geology of the Lake Superior Region. U. S. Geol. Surv., Mon. LII: 513–516, 1911; Leith, C. K., Lund, R. J., and Leith, A.: U. S. Geol. Surv., Prof. Paper 184, 1935; Sampson, E.: Jour. Geol., XXXI: 571–598, 1923.

silica were derived in solution [14] from an adjacent land mass and deposited either by organic agency or as a chemical precipitate.

Notwithstanding the sedimentary origin of the banded jaspilites etc. in the Lake Superior region, there can be no real justification for accepting such a mode of origin for all banded hematite-quartzites, merely on the basis of their lithological similarity. The writer has elsewhere remarked [15] that banded hematite-quartzites may have various modes of origin. Those derived from banded greenalite rocks of the Mesabi Range differ in their original constituents from the original carbonate of the ribbon jaspers of the Gogebic Range, and from the ferric oxide of the itabirite of Brazil, although all are believed to be sedimentary in origin. Within the writer's own exeprience he has seen exactly similar banded hematite-quartzites which originated in the following ways: (*a*) by the silicification of ferruginous banded shales and tuffs (see later pages); (*b*) by the silicification of fine-banded ferruginous sandstones; (*c*) by the oxidation and silicification of hornblende-schists; (*d*) by the oxidation and silicification of rhyolites; (*e*) by the silicification of a fine fault pug; and (*f*) by the alteration of banded sulphides and shale producing a banded jasper.

These examples serve to emphasize that similarity in banding and composition of these rocks is no criterion that their origin is similar. It also emphasizes that, apart from such clearly sedimentary banded jaspers as those of the Lake Superior region, the varieties mentioned above are all the products of silicification.

In North and East Singhbhum.—It has been pointed out that in East Singhbhum banded hematite-quartzites have been formed by the silicification of ferruginous sediments which originated partly as tuffs. The banding in these rocks represents the original bedding.

The chloritic phyllites are normally very high in iron, containing abundant magnetite, and, along the strike, they may grade

[14] Gruner, J. W.: Econ. Geol., XVII: 448, 1923; Moore, E. S., and Maynard, J. E.: Econ. Geol., XXIV: 272–303, 365–402, 506–527, 1929.

[15] Dunn, J. A.: Mem. Geol. Surv. India, LXIX (1): 208–209, 1937; Proc. Aust. Inst. Min. Met., No. 111: 161, 1938.

into hematite-phyllite, hematite-schist and even hematitic iron-ore. In the papers cited,[16] reasons are provided for the belief that silicification of these sediments was contemporaneous with their deposition (even interbedded conglomerates containing pebbles of the silicified rocks are known), and that some oxidation of the chloritic sediments was also in progress.

During accumulation of the sediments, tuffs, and lavas, they were exposed to sub-aerial oxidation. It is not postulated that the original beds were composed entirely of fine tuff deposited *in situ*. Resorting was widespread, and the ferruginous oxidized land surface material gave rise to fine ferruginous sediments. In North and East Singhbhum and in Mayurbhanj, hematitic rocks are interbedded with sandstone-quartzite. Microscopic examination of some of the iron-ores also in South Singhbhum indicates that part of the hematite was of fine detrital origin. During this volcanic period the activity of thermal waters caused silicification at, and close to, the surface and to some extent, perhaps, at depth, thus giving rise to the banded hematite-quartzites.

In this interpretation of the origin of the banded hematite-quartzites of North and East Singhbhum, the iron-content of these rocks is regarded as inherent in the original material but the silica is regarded as essentially secondary. This silica was not necessarily of magmatic origin but was probably largely taken into solution by the thermal waters during circulation through underlying rocks. Similarly, the bulk of the water was of meteoric origin, but heated by the addition of hot waters or water vapour of magmatic origin. Thus, the process pictured is essentially that known to be a feature of such active thermal regions as Rotorua and Wairakei, New Zealand, and Yellowstone Park in America.

The occurrence of cherts or silicified tuffs and sediments, many of them banded, as an accompaniment of vulcanism is sufficiently well known in many parts of the world not to require recapitulation. In India, examples are known associated with the Deccan

[16] Dunn, J. A.: Econ. Geol., XXX: 646–647, 1935; Mem. Geol. Surv. India, LXIX (1): 202–203, 1937; Mem. Geol. Surv. India, LXIX (2), *in press*.

Traps, and further excellent examples of them in the Vindhyan System have been described by J. B. Auden.[17] He finds that tuffs, shales and fine sandstones have been converted into procellanites that are commonly finely banded and even the ripple markings of the original rocks have been preserved. Auden remarks that the "Silicification is almost certainly solfataric in nature."[18] Interbedded conglomerates (Susnai breccia), derived from these, and deposited in wash-outs, indicate that the silicification was contemporaneous with their deposition.

In South Singhbhum.—Jones[19] and Percival[20] have implicitly accepted the banded hematite-quartzites of South Singhbhum as being of sedimentary origin, and Percival has suggested that they were precipitated from igneous thermal waters poured out on the sea bottom, following the hypothesis outlined by Van Hise and Leith.

Notwithstanding the evidence pointing to the metasomatic origin of the silica in the banded hematite-quartzites of the adjacent area of East Singhbhum, the writer has previously been inclined to accept Jones' and Percival's view of the sedimentary origin of the silica in the much thicker and more continuously laterally extensive banded hematite-quartzites of South Singhbhum, Keonjhar and Bonai. The very extent of these latter quartzites compelled a diffidence in suggesting that the silica here was also secondary. Even although signs of replacement are common in them, the writer remarked in 1936: "it is difficult to insist on such an origin for the whole of this great extent of regularly banded rocks. It must be admitted that a sedimentary origin of these banded rocks in South Singhbhum and adjacent States is quite the best and simplest explanation of their origin, but that further re-arrangement has given an aspect of general

[17] Auden, J. B.: Vindhyan sedimentation in the Son Valley, Mirzapur District. Mem. Geol. Surv. India, LXII (2), 1933.

[18] *Idem.*, p. 156.

[19] Jones, H. C.: The iron-ore deposits of Bihar and Orissa. Mem. Geol. Surv. India, LXIII (2), 1934.

[20] Percival, F. G.: The iron-ores of Noamundi. Trans. Min. Geol. Inst. India, XXVI (3), 1931.

replacement at many places." [21] It was suggested that these extensive banded hematite-quartzites of South Singhbhum were deposited in a great lake or sea basin, the iron derived from an adjacent lateritic land surface and the silica leached from below, brought up with thermal waters and emitted over the lake or sea bottom.[22] Where silica was absent, ferruginous shales were deposited.

This view of the origin of the banded hematite-quartzites was expressed at a time when the writer was under the impression that vulcanism was not so characteristic of the Iron-ore Series in South Singhbhum and Keonjhar, as it is in North and East Singhbhum. The recent re-survey has shown that vulcanism was, if anything, even more characteristic of the Iron-ore Series here than in North and East Singhbhum. There is, in fact, nothing in South Singhbhum that is opposed to the views on the origin of the similar rocks as deduced in East Singhbhum—apart from hesitation occasioned by their vastly greater extent in South Singhbhum. But, after appreciating the widespread silicification that has taken place in this area also, the writer is now less hesitant in suggesting this mode of origin also for the banded hematite-quartzites of South Singhbhum.

Thin bands of chert, or silicified tuffs, are sometimes seen within the lavas. In places the lavas themselves have been silicified to red, green or mottled jasper. Tuffs immediately underlying the banded hematite-quartzites at Noamundi mine, and elsewhere, have been irregularly replaced, in places in quite small patches, to red, white, mottled or even green cherts and jaspers. A coarse banding is sometimes noticed in them, particularly close to the banded hematite-quartzites, and they do in fact grade to the latter—close to the junction with the thick banded jaspers or hematite-quartzite there is a certain amount of alternation of tuff and banded jasper.

The thin-bedded tuffs themselves are, at Noamundi, altered to thin-banded hematitic " shales," which, in places, are so rich in

[21] Dunn, J. A.: Mem. Geol. Surv. India, LXIX (1): 206, 1937.
[22] *Idem.*, p. 207.

hematite that they are mined as iron-ore. The banding in these is identical in every way with that in the banded hematite-quartzites.

A rough secondary banding has been seen sometimes in altered lavas below the tuffs, but this is not comparable with the fine even bedding in the tuffs and banded hematite-quartzites.

Admitting the sedimentary nature of the banding in the banded hematite-quartzite, it appears probable that the cherty silica is, however, secondary. Where the original bedding was thin and close, the resulting jasper would be thin-banded. Where the original beds were more massive and less ferruginous, massive white cherts would result.

Silicification of the type suggested is found also in the later Kolhan basal fine-banded sandstone, producing in places an almost cherty material which, where ferruginous and fine-grained, is very similar indeed to the banded hematite-quartzite.

The original nature of the iron is, perhaps, still debateable. Some geologists have suggested that it was in the form of siderite,[23] on the grounds that minute rhombohedra of carbonate are occasionally found in these rocks. However, such isolated carbonate rhombohedra are also seen at times in the tuffs and cherts not associated with the ores and are of secondary origin.[24] In the tuffs the iron was originally in the form of ferromagnesian minerals, which were oxidized to Fe_2O_3, and in ferruginous normal sediments the iron was probably deposited as oxide.

It must be confessed that, although evidence of the secondary origin of the silica is so widespread, there is no evidence in South Singhbhum and Keonjhar denying the sedimentary origin of the silica, either as a chemical precipitate or organically deposited. Even if the silica were deposited from magmatic waters poured out on a sea floor as pictured by Van Hise and Leith, silicification of the immediately underlying beds through which the magmatic waters had passed might also be expected—in other words, silicification would be a minor accompaniment of sedimentary deposition from magmatic waters.

[23] Spencer, E.: Trans. Min. Geol. Inst. India, XXVI (4): 326, 1932.
[24] Dunn, J. A.: Mem. Geol. Surv. India, LXIX (1): 205–206, 1937.

ORIGIN OF THE ORES.

The iron-ores represent, mainly, enriched areas of the banded hematite-quartzites. The process and period of this enrichment may be discussed.

The fact that, in places, the Kolhan conglomerate contains pebbles of iron-ore in addition to pebbles of banded hematite-quartzite indicates that enrichment had already taken place before deposition of the conglomerate. In places this conglomerate is so rich in iron-ore pebbles that it, itself, becomes an iron-ore and has been mined as such. These pebbles might, however, have been shed from (*a*) ore formed prior to metamorphism and folding of the Iron-ore Series sediments, or (*b*) ore formed as a result of surface enrichment on the land surface in Kolhan and pre-Kolhan times.

(*a*) Microscopic examination of the massive ore invariably shows the presence of magnetite, although this is now almost entirely replaced by hematite. At Gorumahisani, in Mayurbhanj State, the banded hematite-quartzites have been metamorphosed, in pre-Kolhan times, to banded magnetite-grunerite rocks, the bands of magnetite and grunerite representing the relative bands of iron-oxide and silica in the original banded hematite-quartzite. Some is entirely of magnetite (now much replaced by hematite), so that the premetamorphic character of the enrichment here is obvious. On the view that oxidation and silicification of these beds to form banded hematite-quartzite was more or less contemporaneous with their deposition, it may also be inferred that the same processes gave rise to local enrichment of iron-oxide.

(*b*) Immediately below the Kolhan conglomerate there are several sections in which the Iron-ore Series lava has been oxidized and enriched to form small local patches of rich hematite. Below the Dhanjori conglomerate in East Singhbhum cases of chloritic tuffs grading to hematite-rock have been observed. There is, then, reason for inferring that surface enrichment of the banded hematite-quartzite did take place on the Kolhan land surface, just as it is taking place at the surface to-day.

The presence of a much later ferruginous grit containing grains of iron-ore in the Iron-ore Series area, and probably Tertiary in age, indicates that the iron-ore beds were again exposed at the surface, permitting probable further surface enrichment.

Apart from the widespread formation of laterite, surface enrichment is taking place at the present time. At all levels from ridge tops at 2,000 feet down to river level at 1,200 feet, there are cemented deposits of conglomerate, *Canga* (distinct from hill debris or "float-ore"), generally consisting of iron-ore pebbles cemented by hematite or limonite, and some are sufficiently rich to be mined as iron-ore. This cementation, or partial enrichment, is clearly post-Tertiary to Recent in age. The banded hematite-quartzites and associated ferruginous beds, are commonly enriched to massive steely ore at the contoured surface of the ridges, or massive hard steely ore may grade to soft porous ore within a few feet below the surface. In many places a superficial skin of hard ore may give place to fine loose "blue dust" in a few feet, this hard ore apparently representing a cementation skin over the blue dust. This process is taking place to-day, and there are no grounds for inferring that such surface enrichment is caused by other than cold meteoric waters.

There is, then, evidence that enrichment to form these iron-ore bodies has not been a single process, but has taken place from time to time since the associated beds were first deposited whenever the conditions have been suitable. It is probable that the early enrichment during deposition of the Series, was caused by hot waters, but there are no grounds for believing that the later enrichments, associated with periods of surface oxidation, were the accompaniment of other than cold circulating meteoric waters.

The origin of the "blue dust," which so generally accompanies these ores, requires discussion. It shows all the fine banding, minute puckering and faulting and even recumbent folding, of the banded hematite-quartzite—indeed in the exposed quarry faces it appears at first glance to be normal banded hematite-quartzite, but on being touched with a stick, it runs down as a fine loose dust of hematite with some fine quartz. It may be traced into

normal hard banded hematite-quartzite, just as also may some of the porous ore, and has been formed by desilication of banded hematite-quartzite. It is believed that this desilication is more or less Recent in time. It is certainly post-Kolhan, as strong post-Kolhan fold movements were locally prevalent in the area, and such loose material could not have retained all its minute structure unimpaired through any period of strong movement. Tertiary movements were also strong in this part of the Peninsula and it is in view of these considerations that the desilication to form the blue-dust is regarded as Recent. This does not deny desilication as an important factor in earlier enrichment, but if such desilicated ore existed, it has been long since re-cemented.

Under what conditions circulating waters have been responsible for desilication, in contrast to the silicification that gave rise to the cherts, is a matter of speculation. Two determining factors may be suggested: drainage and local degree of acidity or alkalinity.

CONCLUSION.

Most geologists who have had wide experience of the iron-ores of the type described herein, believe that the rhythmic banding in the associated jasper-quartzites is of sedimentary origin. There have been two main general views of the origin of these banded quartzites, to which the writer would add a third:

1. The view first proposed by Van Hise and Leith that the silica and ferruginous material were deposited from submarine magmatic springs which poured out their iron and silica content on the sea floor.

2. The view that the iron and silica were brought in solution from a neighbouring volcanic land mass and rhythmically deposited as sediments in water, probably in consequence of seasonal variations of composition of the water. The mode of deposition has been variously explained, usually by direct chemical precipitation of silica and ferrous constituents, or by organic agency.

3. The writer's view, that the beds were originally deposited as fine-bedded ferruginous tuffs (which became oxidized), and

more normal ferruginous sediments, and that surface and subsurface silicification of these, more or less contemporaneous with their deposition, under the action of solutions partly magmatic in origin, gave rise to the banded jaspers and cherts. The cherty nature of the silica was determined by the low temperature condition of deposition.

The writer does not deny the probability of the sedimentary origin of the cherty silica, but points out that there is no direct evidence in support, whereas examples of silicification of the associated banded sediments are numerous.

Enrichment of the ores cannot be attributed to any one period, but took place at any time that the conditions were favorable. There have been at least three such favorable periods: (*a*) during the formation of the beds, (*b*) immediately preceding deposition of the Kolhan Series, and (*c*) during Tertiary and Recent times.

The writer holds no particular views as to whether hot or cold waters were responsible for enrichment. Possibly waters approximating 100° C. were responsible for the original silicification and enrichment, but cold (or warm) circulating meteoric waters appear to have been responsible for more recent enrichment. Alkalinity and acidity would be the deciding factor rather than temperature.

Enrichment has been brought about by two main processes—(*a*) replacement of silica by iron, and re-cementation, and (*b*) desilication. In the former case iron is added, mostly at the expense of silica, in the latter case merely silica is removed, leaving either a porous ore or a powder ore.

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PARAGENETIC RELATIONS IN THE SILVER ORES OF ZACATECAS, MEXICO.

EDSON S. BASTIN.

ABSTRACT.

Microscopic study of a large suite of specimens from the famous Mexican silver camp of Zacatecas shows that the *prevailing* order of deposition among the hypogene minerals was (1) pyrite, (2) sphalerite, (3) quartz, (4) nearly simultaneous deposition of tetrahedrite, galena, chalcopyrite and argentite, (5) sulphantimonides of silver, (6) calcite. Individual specimens show departures from this general sequence. The silver minerals of the rich ores are interpreted as in the main late hypogene. There seems to be no evidence of more than a single period of hypogene mineralization. Native silver and some argentite occur as supergene minerals in the zones of oxidation and enrichment. A little cerargyrite occurs in oxidized ores.

INTRODUCTION.

THE remarkably rich silver ores of the Zacatecas district in the State of that name played a spectacular rôle in the mining history of Mexico from the time when mining began in 1548 until the beginning of the present century. In the 339 year period between 1548 and 1888 the value of its output has been estimated at 878 million pesos.

This paper is not a comprehensive study of the geology of the district and in the present state of complete decadence of mining in the district such a study would face many handicaps. There is available, however, in the United States National Museum a considerable collection of rich silver ores from Zacatecas, many of them collected in the days when mining was active. As no studies seem to have been made of the paragenesis of the Zacatecas ores, it seemed worth while to study them as a contribution to the geologic history of one of the world's most famous silver camps. Most of the specimens studied were loaned by the U. S. National Museum through the courtesy of Dr. W. F. Foshag; a few were in the University of Chicago collections. The technique included

the study of all the specimens under the binocular microscope and the examination of polished pieces of the most suitable specimens under the metallographic microscope.

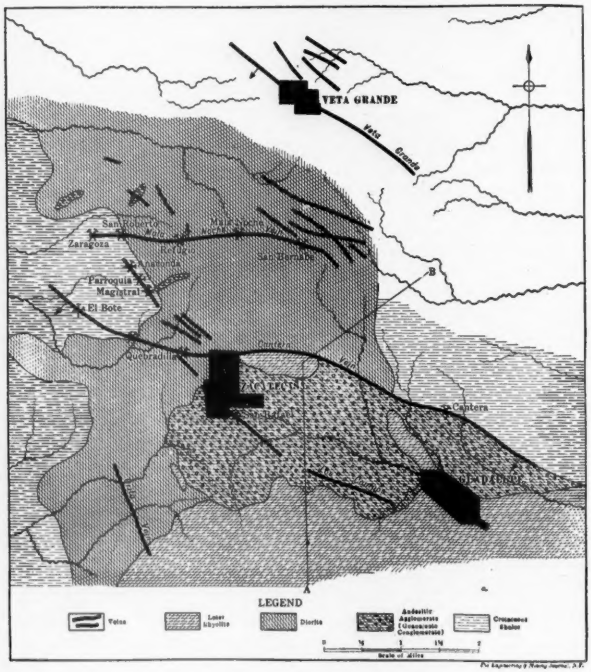


FIG. 1. Veins of the Zacatecas district, after Botsford.

For more general information on the geology of the district the reader is referred to the descriptions of Burckhardt and Scalia [1] and those of Flores [2] in the Guide to the Tenth International Geological Congress.

[1] Burckhardt, C., et Scalia, S.: Géologie des Environs de Zacatecas. Guide des Excursions X Congrès Geologique International, 1906.

[2] Flores, T.: Étude Minière du District de Zacatecas. Guide des Excursions X. Congrès Geologique International, 1906.

The map showing the veins of the district that forms Fig. 1 is reproduced from an article by Botsford.[3]

CRITERIA OF PARAGENESIS.

Although this is not the place for general discussion of the criteria of paragenesis, it is appropriate that those criteria that have been principally relied upon in this study should be stated before the results of their application are given.

Automorphic Outlines.—If the contacts of two crystalline minerals are in the main sharp and straight they probably represent crystal faces of one mineral or the other. Two alternatives then

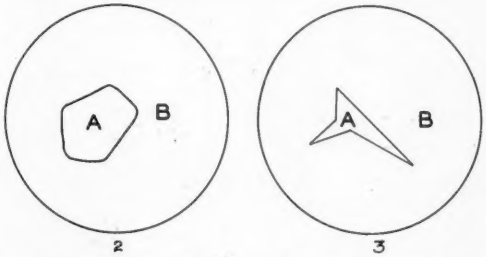


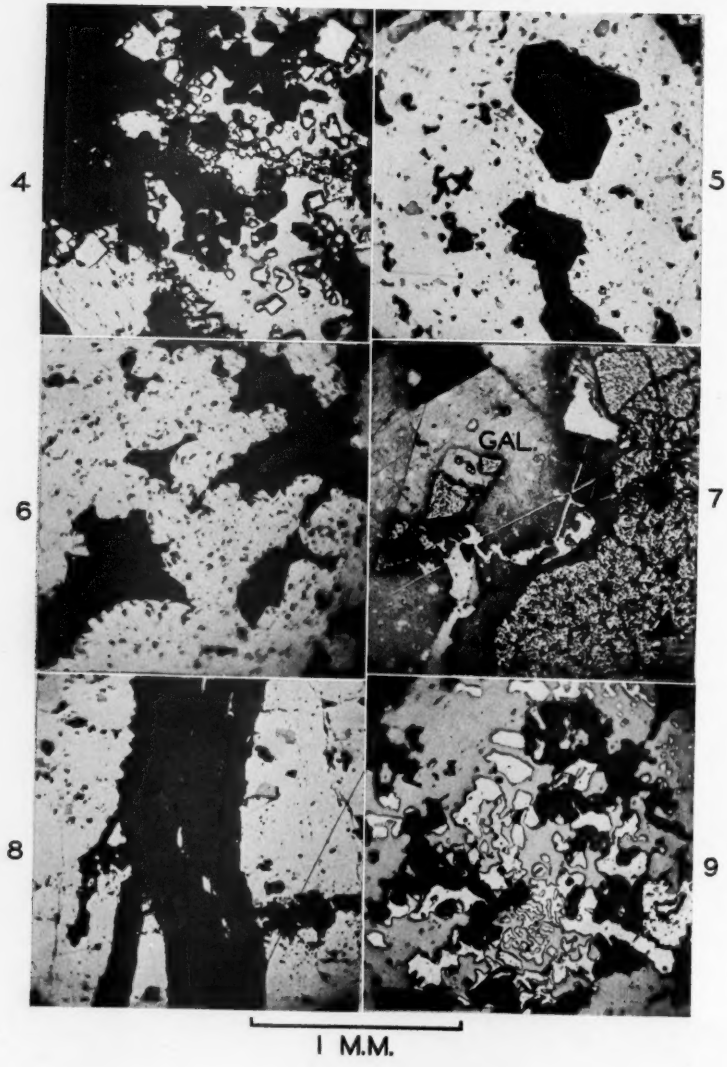
FIG. 2. The outlines of mineral A, which are "convex" or protruding towards mineral B, indicate that A is probably older than B.

FIG. 3. The outlines of mineral A, which are "concave" towards mineral B indicate that its boundaries are crystal faces of B and that A is the younger.

exist: (1) one mineral may be an automorphic replacement of the other or (2) the minerals may have been deposited in succession, the younger mineral conforming to the crystal outlines of the older. It is generally good practice to avoid the first or replacement alternative unless definite evidence of replacement can be found, for even automorphic replacement usually betrays itself by spacial relations to fractures, by selecting certain minerals as host, or in other ways.

In the absence of evidence of replacement, successive deposition must be postulated and the question then is which of the two

[3] Botsford, C. W.: The Zacatecas District and its relations to Guanajuato and other camps. Eng. and Min. Jour., 87: 1227–1228, 1909.



FIGS. 4–9.

minerals is the older. If mineral *A* shows crystal outlines characteristic of itself but not of mineral *B*, the problem is very simple. This is the case, for example, in Fig. 4 in which older pyrite shows its characteristic cubical outlines against both quartz and chalcopyrite and quartz shows its characteristic hexagonal outlines against chalcopyrite. Similarly in Fig. 5 older quartz shows its characteristic hexagonal outlines against younger freibergite.

In other cases the problem is less simple but may still be solved. As shown in Fig. 2, mineral *A* may not show outlines certainly identifiable as of that mineral but its general outline is *convex* outward and its crystal faces join to enclose an isolated grain of *A* in *B*. It is highly probable that the crystal faces are those of mineral *A* rather than mineral *B* and therefore that mineral *A* is older than *B*. In Fig. 3, however, mineral *A* has crystal boundaries that in general are *concave* outward and it is probable that these are crystal faces of mineral *B* rather than *A*. Good examples of "concave" areas of a younger mineral in an older are shown in Fig. 6. Such areas although described for brevity as "concave" are bounded wholly or in part by crystal faces and must not be confused with the caries [4] developed by replacement.

[4] Bastin, E. S. and others: Criteria of age relations of minerals with especial reference to polished sections of ores. ECON. GEOL., 26: 589, 602, 1931.

FIG. 4. Ore from San Jesus mine showing cubical pyrite (white) automorphic towards quartz (dark) and chalcopyrite (light). The order is pyrite, quartz, chalcopyrite.

FIG. 5. Ore from San Jesus mine showing quartz crystals (dark) automorphic to freibergite (white). Inclusions of sphalerite (gray) occur in the outer portions of both.

FIG. 6. Ore from the Carmen mine showing quartz (dark) conforming to outlines of older sphalerite (light) which in part are straight crystal faces and in part rotund as is characteristic of sphalerite.

FIG. 7. Ore from the Guadalupe mine (145 m.) showing galena (gal.) partially replaced irregularly and along cleavage planes by freieslebenite (light gray); rough gray is pyrite. The galena has been tarnished with hydrogen peroxide.

FIG. 8. Ore from San Jesus mine showing branching veinlet of calcite (dark) traversing freibergite which in upper left is automorphic towards calcite.

FIG. 9. Graphic intergrowth of galena (white) and sphalerite (light gray). The dark gray is quartz, which is older than the minerals of the intergrowth. Carmen mine, 150-foot level.

It sometimes happens that even in the same field of the microscope mineral *A* in places shows its own characteristic crystal outlines against mineral *B* and that a short distance away the relations are completely reversed. In many such cases there is no evidence of more than one generation of *A* or of *B*. Such cases must be interpreted as indicating simultaneous crystallization of *A* and *B* with mutual interference. Such an interpretation is often harmonious with paragenetic evidence of a chemical sort, as in the case of intercrystallizations of cuprite and native copper that developed as simultaneous oxidation products of chalcocite.

Inclusions.—Small inclusions of one mineral in another in the ores of Zacatecas must be differently interpreted in different cases. Minute inclusions of chalcopyrite in sphalerite, many of them oriented in lines parallel to crystallographic directions of the sphalerite, are probably in most cases due to the unmixing of a solid solution of the two sulphides.[5] The two minerals must be interpreted as contemporaneous.

Inclusions that must be given a very different interpretation are shown in Fig. 5. In that figure rows of inclusions of sphalerite may be seen in the outer portions of the quartz crystals and roughly paralleling the crystal faces. Sphalerite inclusions are also abundant and reach larger sizes in the bordering freibergite. These relations are interpreted as indicating that sphalerite began to deposit late in the period of quartz deposition and continued into the period of freibergite deposition.

Veinlets.—Minerals of veinlets are in nearly all cases to be interpreted as younger than the minerals that the veinlets traverse. The method of emplacement may be either replacement as in Fig. 7 or fracture filling. Their sheet-like form is consequent upon linear features of the host such as fractures, mineral cleavage, partings, or mineral contacts. Some veinlets, however, present perplexing features. In Fig. 8 is shown a branching veinlet of calcite in freibergite and distinct fragments of freibergite occur in the veinlet. In many places the vein walls are so straight and regular that it is reasonable to interpret them as marking the posi-

[5] Schneiderhöhn, H., und Ramdor, P.: Lehrbuch der Erzmikroskopie. Zweiter Band, 106–110, 1931.

tion of fractures in the freibergite. In places, however, as in the upper left of Fig. 8, automorphic crystals of freibergite form the wall of the veinlet. This appears to indicate growth of freibergite crystals after the fractures had formed and about contemporaneous with the introduction of the calcite. The fracturing took place, therefore, *during* the mineralization, an interpretation that is supported by the fact that in places, as shown in the lower right hand portion of Fig. 8, the calcite veinlet is continuous with irregular intergrowths of calcite and freibergite.[6]

PARAGENETIC DIAGRAMS.

In the paragenesis diagrams here used the minerals are listed from top to bottom in the order in which their crystallization appears to have *begun* with the qualification that minerals that are strictly contemporaneous are obviously interchangeable in position.

The relative positions of the lines indicate whether the periods of deposition of the minerals were contemporaneous or overlapped. The total width of the diagram is adjusted to the width of the printed page so that in some diagrams involving many minerals the lines are short, while in others they are long. All that is consequential is the relative positions of the lines.

In the following pages the ores from individual properties will first be described and a summary and discussion of general relationships will conclude the paper.

DESCRIPTIONS OF ORES FROM INDIVIDUAL MINES OR VEINS.[7]

San Rafael Mine.—As shown on Fig. 1, this mine lies in the southern part of the town of Zacatecas and develops the San Rafael vein, which appears to be a branch from the Cantera vein system. A single specimen (91527) from this mine shows the mineral sequences indicated in Diagram 1[8].

[6] It may be noted in passing that not all veinlets bordered by automorphic crystals of their wall material are to be explained in this way. Some represent simple crustification and some may be due to subsequent crystallization of materials originally deposited in colloidal form.

[7] Numbers in parentheses are U. S. National Museum specimen numbers.

[8] Diagrams 1–23 represent paragenetic sequences of ores from mines indicated.

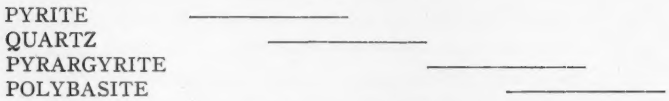


DIAGRAM 1. Paragenetic diagram. Ore from San Rafael mine, depth not reported.

Both pyrargyrite and polybasite are younger than quartz, which they cap in vugs, but crystallization of polybasite seems to have persisted longest. All the minerals of this ore are interpreted as hypogene. Depth from which specimen came was not specified.

La Cantera Vein.—According to Flores[9] this is the longest and most conspicuous vein in the district and occupies a fault zone of considerable width and displacement (Fig. 1). Its average strike is N. 78° W. and its dip 50° S.W. and its position is marked by prominent crests on the hills of the district. Its width varies from 5 to 40 meters and it has been traced in length for about 11 km.

In spite of its conspicuous character La Cantera vein is barren of valuable ore except where cut by N–S fractures which intersect it almost at right angles. A single specimen (92344) from this vein showed the paragenetic relations given in Diagram 2. The

DIAGRAM 2. La Cantera fluorite-bearing ore.

presence of fluorite as a late mineral, probably hypogene, is noteworthy for it was not noted in any of the other specimens studied from Zacatecas.

San Martine Vein.—On San Martine hill, according to Flores,[10] the outcrop of La Cantera vein enlarges notably and the branch

[9] Flores, T.: Op. cit., pp. 9–18.
[10] Flores, T.: Op. cit., pp. 9–10.

vein San Martine makes off in a N. 47° W. direction with a dip of 43° SW.

Two specimens in the University of Chicago collections labelled San Martine, Zacatecas, Mexico, evidently came from this vein. Although the depth was not recorded it is evident from the presence of a little limonite that both came from the lower part of the zone of oxidation.

The first specimen is a heavy sulphide ore with galena crystals, prevailingly in skeletal forms, from 2 to 3 cm. across. Small vugs are common, some being lined with crystals of quartz, galena and sphalerite, and others contain colorless calcite and dolomite as late minerals. In the polished specimen under the microscope the mineral sequence shown in Diagram 3 was observed.

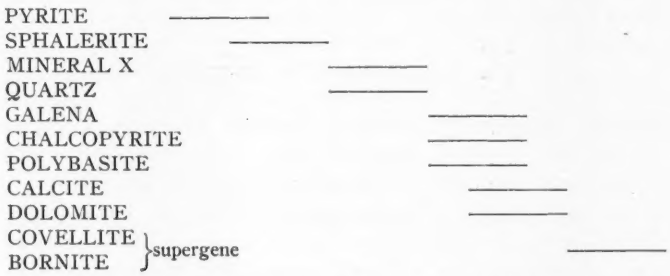


DIAGRAM 3. San Martine ore, probably from near original water table.

Sphalerite is automorphic with respect to all other minerals except part of the pyrite and hence is older. This age interpretation is confirmed by the rare occurrence in sphalerite of tiny segmented veinlets composed of one or more of the minerals quartz, mineral X,[11] galena, chalcopyrite, and polybasite.

Polybasite is present sparsely in small grains whose relations to other minerals are identical with those shown by galena and chalcopyrite. It is therefore interpreted as hypogene.

[11] Mineral X is a non-metallic between 5 and 6 in hardness and anisotropic in polarized reflected light. It occupies the same relationship to other minerals that quartz does. A thin section would be necessary for its identification.

Small amounts of covellite occur as peripheral replacements of chalcopyrite and of polybasite, the only hypogene copper-bearing minerals of the ore. Minute amounts of bornite occur as peripheral replacements of chalcopyrite. These are interpreted as supergene replacements representing the early stages of copper enrichment.

The second specimen from this mine is not suitable for the preparation of polished specimens. Minerals present are light-brown sphalerite, quartz (in part amethystine), chlorite,[12] argen-

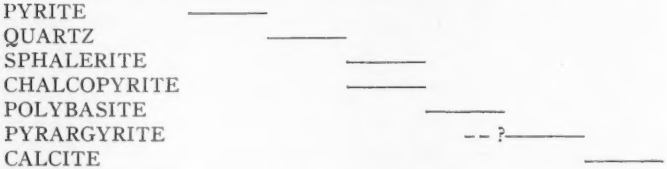


DIAGRAM 4. El Bote ore, 800-ft. level.

tite, and native silver. Crystals of native silver up to 1 mm. across were noted on quartz in vugs. In places capping the native silver but elsewhere alongside it are star-like, radiating, crystal aggregates of argentite. This mineral also forms lichen-like incrustations on quartz and chlorite, some of which pass at their peripheries into the delicate star-like argentite crystals. These relations do not suggest a derivation of the native silver from the argentite but instead a nearly simultaneous deposition of the two minerals. The two silver minerals may be late hypogene or supergene but are more probably supergene.

El Bote Veins.—El Bote mine is situated nearly 2 miles due west of the city of Zacatecas on El Bote hill (Fig. 1). According to Flores [13] the veins developed in this mine belong to the east-west system and lie in the old sericite schists. Their general trend is N. 65° W. with dips of 65° to 80° S.W. They join La Cantera

[12] Soft, greenish-gray, sectile, with radiating fibrous habit. Color in thin plates under the microscope is brownish-green. Pleochroic. Parallel or nearly parallel extinction. Index of refraction by immersion method close to 1.607.

[13] Flores, T.: Op. cit., p. 13.

vein near the San Jorge shaft. Their outcrops are well-defined and have an average width of 3.5 meters and are easily distinguished from La Cantera outcrops by their different constitution, notably by the abundance of iron oxides.

Three specimens from El Bote were studied. The nature of the hypogene mineralization is best shown in a specimen (91140) collected by F. L. Ransome in 1906 from the 800 foot level. Diagram 4 shows the sequence of deposition as revealed in the polished specimen of this ore. In addition to the minerals visible in the polished specimen the hand specimen shows argentite. This mineral is younger than quartz on which it has been deposited in vugs. It occurs side by side with polybasite and there is no indication that it is an alteration product of the latter. Calcite is younger than the rich silver minerals coating them in certain vugs. Chalcopyrie in places conforms to the crystal outlines of sphalerite; in other places the reverse relation is seen and in still other places the mutual contacts are smoothly curving. The two minerals are interpreted as contemporaneous. Polybasite and pyrargyrite occupy vugs in quartz and conform to the crystal outlines of the latter. In most places pyrargyrite conforms to the crystal outlines of polybasite; elsewhere it contains inclusions of polybasite or penetrates it in tongue-like projections. It is possible that the deposition of the two minerals overlapped somewhat.

Of two small hand specimens from El Bote, one (44391) is almost wholly native silver. In the other, quartz is coated with polybasite and numerous "teeth" of native silver grow out of the polybasite and are clearly an alteration product of it. Where silver is most abundant, polybasite has completely disappeared. These specimens evidently came from the lower part of the zone of oxidation because in places green copper stains are present.

Another hand specimen (44343) from this mine shows polybasite, pyrargyrite and a little argentite deposited on the crystalline quartz of vugs. The quartz shows the forms characteristic of the low temperature variety (formed below 573° C.). There is no oxidation and no development of native silver.

It is noteworthy that some of the ores of El Bote are auriferous although no gold was seen in the few specimens studied. Ac-

cording to Halse[14] gold also occurred in the Australia mine located on an extension of one of the Bote veins. According to the management, the gold tenor varies from 0.5 to 1.5 ounces. The gold is said to occur free in close association with argentite.

Calycanto Mine.—This mine is located about 2 km. northwest of the city of Zacatecas.

Four specimens were available for study. The depth from which they came was not recorded but none showed any oxidation. The first specimen was composed of pyrite, sphalerite, galena, and a little quartz but seemed to carry no rich silver minerals. The second specimen shows a very fine-grained greenish-gray rock traversed by a network of minute veinlets whose principal component is pyrargyrite though minor amounts of pyrite are also present. In the third specimen similar rock, carrying disseminated pyrite grains, is traversed by small veinlets of pyrargyrite and white calcite. In the fourth specimen an association of pyrite, sphalerite, quartz, and galena is traversed by veinlets of pyrargyrite and calcite. All of the minerals of these ores are interpreted as hypogene.

Mala Noche Vein.—Although the largest vein of the east-west system, La Cantera, is in the main barren, other veins of this system, occupying faults of lesser displacement, have been highly productive. One of these is the Mala Noche vein (Fig. 1) lying about 3 km. north of La Cantera. According to Flores[15] this vein is traceable for about 5 km. with an average strike of N. 87° E. and a dip of 65° NW. The vein is represented in the collections studied by specimens from the Mala Noche and Refugio mines.

The *Mala Noche* mine is represented by two specimens from unrecorded but evidently slight depths since both show the development of native silver by the oxidation of argentite. One specimen (57055) shows early hypogene associations of quartz, pyrite, sphalerite, and galena. In small vugs in this material calcite and argentite were deposited presumably as the last episode

[14] Halse, Edward: Notes on some gold-bearing veins of Zacatecas, Mexico. Eng. and Min. Jour., 58: 75, 1894.

[15] Flores, T.: Op. cit., pp. 4–5.

in the hypogene mineralization. Finally as the result of supergene oxidation of its sulphur some of the argentite has been altered to native silver, tapering, curling "teeth" of which grow directly out of the argentite.

A second specimen (57056) evidently came from the wall of an open veinlet. The wall-rock is coated mainly with pyrite in crystals up to 5 mm. On the pyrite in places rhombs of white calcite have been deposited and on both pyrite and calcite dendritic growths of crystalline native silver have been deposited. Thin coatings of argentite also encrust some of the pyrite and calcite. Some rhombs of calcite look as if they had been painted black by the deposition of a thin crust of hematite. Although hematite was not observed in contact with the siver, it is similarly related to pyrite and calcite and is probably of about the same age as the silver. Paragenetic relations are interpreted in Diagram 5.

DIAGRAM 5. Mala Noche ore.

As some of the hematite has altered to limonite the specimen probably came from the lower part of the oxidized zone.

The *Refugio mine* is represented by one specimen of coarse pyrite with a little accessory sphalerite, galena and quartz.

Nuevo Granada Mine.—This mine is located in the Veta Grande area lying a few kilometers north of the main productive area of the Zacatecas district.

A single specimen (57030) from an undesignated depth contains abundant tetrahedrite. The mineral sequence as observed in the polished specimen is shown in Diagram 6. Chalcopyrite occurs as inclusions in the tetrahedrite or the two minerals may be in fine graphic intergrowth. In the absence of any evidences of replacement the graphic texture is interpreted as indicating contemporaneous crystallization. Where galena borders tetrahedrite

it may conform to the crystal outlines of the latter or the two may be in fine graphic intergrowth, relations that indicate overlap in deposition. Calcite traverses tetrahedrite in well-defined veinlets some of which connect with irregular calcite areas occupying the interspaces between crystals of both galena and tetrahedrite.

DIAGRAM 6. Nuevo Granada ore.

Calcite may be automorphic against galena or the relation may be reversed. The two minerals are interpreted as contemporaneous.

Guadalupe Mine.—Four specimens from the Guadalupe mine at Veta Grande came from depths of 125 to 417 meters. A specimen (57027) from the 217-meter level shows only hypogene minerals whose paragenetic relations are interpreted in Diagram 7.

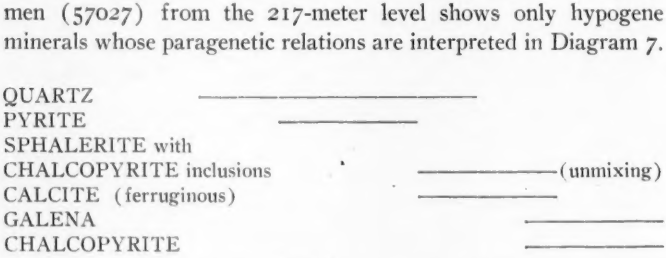


DIAGRAM 7. Guadalupe ore, 217 m. level.

No sliver minerals were noted and no replacement phenomena. The calcite is evidently slightly ferruginous since it becomes somewhat brownish on weathering. In a specimen (57023) from a depth of 125 meters in the Ste. Tomás shaft, pinkish-gray felsite was traversed by sub-parallel fractures along which quartz, pyrargyrite and calcite, named in order of age, have been deposited. Calcite was the last to deposit. In a specimen (57024) from the 214 meter level, pyrargyrite was associated with tetrahedrite, the entire paragenetic sequence being interpreted in Diagram 8. The

tetrahedrite is younger than the quartz but older than most at least of the pyrargyrite crystals for the latter cap the tetrahedrite. This seems to be a simple depositional sequence not complicated by replacement and all of these minerals are interpreted as hypogene.

DIAGRAM 8. Guadalupe ore, 214 m. level.

A specimen (57028) from a depth of 145 meters in the Ste. Tomás shaft displays interesting selective replacements of galena by freieslebenite ($2Ag_2S.3PbS.2Sb_2S_3$), which are pictured in Fig. 7. The sequence of deposition is interpreted in Diagram 9. Except for rare inclusions of sphalerite in galena there is no overlap among the first five minerals, each in succession conform-

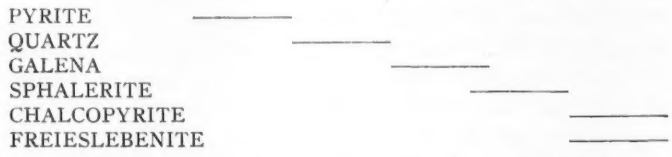


DIAGRAM 9. Guadalupe ore, Ste. Tomás shaft, 145 m. level.

ing completely to the crystal outlines of the preceding minerals in the list. Freieslebenite by repeated tests gives all the etch reactions listed by Short for that mineral. It is close to galena in color but slightly harder and anisotropic, its polarization colors being light, dark and brownish gray. Hydrogen peroxide tarnishes the galena but does not affect the freieslebenite. After such treatment the freieslebenite can be seen to occur mainly as small veinlets traversing galena and invariably following cleavage directions. These veinlets are of uneven width with walls that do not "match" and are interpreted as typical replacement veinlets. A few of the freieslebenite veinlets show sudden bulbous enlarge-

ments, another symptom of replacement origin. Less commonly freieslebenite occurs in irregular areas that show ragged boundaries against galena, indicative of replacement. Some of the veinlets join these less regular areas.

Selective replacements of galena by freieslebenite such as has just been described might be either late hypogene or supergene in origin. Because of their relations to chalcopyrite, a typically hypogene mineral, they are believed to be late hypogene. Chalcopyrite in part conforms to the crystal outlines of all other minerals except freieslebenite, but a few replacement veinlets of chalcopyrite make off from the larger areas and penetrate galena along its cleavage directions. It is significant that some of these chalcopyrite veinlets are continuous along their trend with freieslebenite veinlets.

The only supergene mineral observed in the Guadalupe ores was native silver in a specimen (57020) labelled, probably erroneously, as from the 417 meter level. This ore is composed mainly of pyrite with which is associated a little sphalerite. White dolomite conforms to the crystal outlines of pyrite and in places traverses it as small veinlets. In some vugs in the dolomite are small ruby-red crystals of pyrargyrite and some of quartz. In other vugs mats of tapering and coiling "teeth" of silver lie on the pyrite and dolomite. The tooth-like form indicates that they are secondary after some silver compound, possibly argentite, that originally occurred in the vugs. The silver is tarnished surficially dark gray to golden yellow but is silver-white within.

San Borja Mine.—Seven specimens from this mine were studied under the binocular microscope, none being suited for the preparation of polished specimens. Although the depths from which these specimens came were not recorded, most of them carry wire and "teeth" of native silver and therefore came from the zone of oxidation. Several of these specimens are obviously low grade carrying only pyrite, chalcopyrite, sphalerite, galena, and quartz. In other specimens, however, rich silver minerals occur in vugs and in fractures traversing the quartz and base-metal sulphides. These include argentite, pyrargyrite, and a

black, brittle silver mineral too sparse for full determination but probably polybasite. As far as the evidence from the specimens goes, these rich silver minerals might be either supergene or late hypogene. Analogy with ores from other mines favors a late hypogene origin.

In many of the specimens wires and tapering " teeth " of native silver occur. In places these rest on argentite or pyrargyrite or

DIAGRAM 10. Carmen rich silver ore.

polybasite (?) and are clearly products of their oxidation. In one specimen cerargyrite has developed apparently as a direct alteration of argentite.

Carmen Mine.—Three specimens from the Carmen mine were studied. One specimen (57032), whose depth of occurrence was not recorded, is mainly an aggregate of quartz and fine-grained pyrite, these two minerals being approximately of the same age.

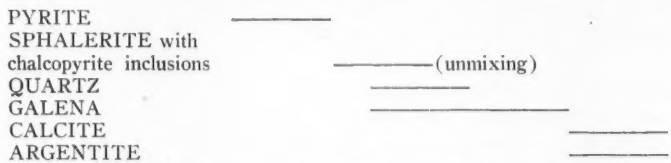


DIAGRAM 11. Carmen ore, 150 m. level.

In what were evidently quartz-lined vugs and fractures in this material occur pyrargyrite, miargyrite,[16] and calcite. The miargyrite conforms to the crystal outlines of pyrargyrite and is therefore slightly younger. The paragenetic sequence is shown in Diagram 10.

A second specimen (57052) came from the 150 meter level and shows the sequence of minerals illustrated in Diagram 11. Well

[16] Miargyrite identified by conformity to the etch tests given by Short and also by the polarization colors, white, blue-gray and brownish.

crystallized argentite occurs in quartz-lined vugs associated with scalenohedral calcite. The argentite and calcite generally are side by side but in places are intergrown in such a fashion as to indicate that the two minerals were crystallizing simultaneously. If this is true the solutions depositing the argentite could not have been acid. Minute inclusions of chalcopyrite are very abundant in sphalerite and are interpreted as due to unmixing the two min-

DIAGRAM 12. Carmen ore.

erals, therefore being contemporaneous. Galena commonly conforms to the automorphic outlines, often rotund, of sphalerite but in places the two minerals are in graphic intergrowth as shown in Fig. 9. In the absence of any evidences of replacement such intergrowths are interpreted as indicating contemporaneity. The two minerals therefore overlap in age.

In a third polished specimen bearing the same number galena forms about half of the ore and conforms to the outlines of quartz

DIAGRAM 13. Carmen ore; hand specimen shows also pyrargyrite.

and sphalerite. Minor amounts of chalcopyrite and argentite also conform to the outlines of quartz and sphalerite. The boundaries between galena, chalcopyrite, and argentite are smoothly rounding and are not suggestive of any diversity in age. (Diagram 12.)

Two other specimens from this mine, both numbered 57033, are so different from each other as to raise some doubt whether they came from the same locality. They will be separately de-

scribed. The first specimen shows in the polished piece the mineral sequence represented by Diagram 13. Although no silver minerals are visible in the polished specimen, the hand specimen shows pyrargyrite capping quartz in vugs. Pyrargyrite also occurs in lichen-like masses along fractures traversing the base-metal sulphides. In a few places along such fractures the pyrargyrite has altered directly to native silver. The pyrargyrite may be interpreted either as late hypogene or supergene, but the native silver is supergene.

The second specimen under this number has the mineral sequence shown in Diagram 14. It is noteworthy that there is no

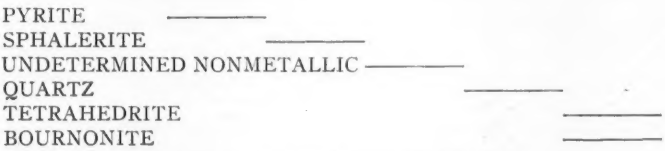


DIAGRAM 14. Carmen bournonite-bearing ore.

galena in this specimen but that lead has entered the sulphosalt bournonite.[17] The undetermined mineral is now apparently finely divided kaolin for its intermediate index of refraction is near 1.565. The nature of the original mineral is indeterminate.

Carniceria Mine.—Eight specimens from depths of 115 to 276 meters in the Carniceria mine were studied. The specimen from 276 meters (57038) is highly silicified rock with disseminated pyrite and a little calcite. It shows no silver minerals and is obviously very low grade.

The remaining seven specimens from depths ranging from 115 to 240 meters show not only base metal sulphides but also rich silver minerals all of which are interpreted as hypogene. No replacement and no oxidation was observed in these ores. Paragenetic relations are best displayed in a specimen (57050) from the 217 meter level as shown in Diagram 15. Some sphalerite

[17] Conforms fully to all the etch reactions listed by Short. Anisotropic in reflected polarized light, colors being light brown and purplish. Slightly softer than tetrahedrite.

is automorphic with respect to quartz but the reverse relation is also common so that the two minerals must be interpreted as essentially contemporaneous. Galena and chalcopyrite are closely associated and show identical relations to other minerals. Small vugs in this ore contain crystals of quartz, calcite, polybasite, and argentite. Calcite conforms to the crystal outlines of the quartz

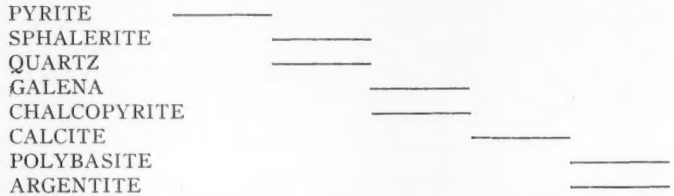


DIAGRAM 15. Carniceria ore, 217 m. level.

but is automorphic towards polybasite and argentite. None of the minerals of this ore seems to have replaced other ore minerals. All are interpreted as hypogene.

A specimen (57045) from the 147 meter level shows argentite and polybasite in vugs neither being an alteration product of the other. Their close association with unetched crystals of calcite shows that they were not deposited under acid conditions.

DIAGRAM 16. Carniceria ore, 149 m. level.

Another specimen (57047) from about the same depth (149 meters) differs mainly in the presence of pyrargyrite instead of argentite, the paragenetic sequence being shown in Diagram 16. Pyrargyrite was not present in the polished specimen but in the hand specimen seemed to be the last mineral deposited. The poly-

basite of these ores not only gives the etch tests listed by Short, but also shows diagnostic pleochroism in polarized light—violet to greenish-yellow to brown.

A specimen (57044) from the 240 meter level shows argentite coating scalenohedral calcite in vugs. The argentite is mainly a net-like deposit but in places forms a continuous coating preserving the form of the underlying calcite crystals. The argentite is clearly a direct deposit and not an alteration product of some other silver mineral. It may be either late hypogene or supergene. Its association with unetched calcite indicates that it was not deposited from acid solutions.

In a specimen (57043) from the 174 meter level a black, brittle, sulpho-salt of silver occurring in vugs has not the form of polybasite but is in thick prismatic crystals identified as stephanite.

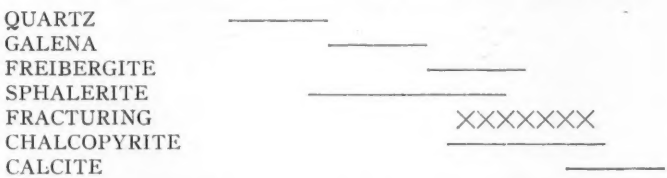


DIAGRAM 17. San Jesus ore.

San Jesus Mine.—The single specimen (57061) available from this mine showed a number of interesting features. The presence of some azurite and malachite as well as yellow and orange oxidation products indicates that it came from the oxidized zone though the depth in meters was not recorded. The sequence of mineral deposition as interpreted from the polished specimen is shown in Diagram 17. Noteworthy is the abundant presence of freibergite[18] or highly argentiferous tetrahedrite. This mineral always conforms to the crystal outlines of quartz and galena. Sphalerite occurs partly as tiny inclusions in the outer portions of quartz crystals and partly as inclusions in freibergite, as is shown in Fig. 5. The sphalerite in quartz is automorphic. That in

[18] Gray metallic of dark reddish-brown streak. Before blow-pipe gives antimony coating. Strong wet tests for copper and for silver.

the freibergite in part shows its own outlines and in part conforms to the crystal faces of freibergite. Evidently sphalerite deposition overlapped both quartz and freibergite as indicated in Diagram 17. Segmented veinlets of calcite and some chalcopyrite traverse all other metallics but are particularly numerous in freibergite. The opposite sides of these veinlets do not match, yet there is no evidence that they are replacement veinlets. In places one side of the veinlet may be fairly straight, as if it followed a fracture, while the other side is irregular and shows numerous automorphic crystals of freibergite projecting into calcite (Fig. 8). Some of the unsymmetrical veinlets join up with irregular mesh-works of calcite enclosing automorphic freibergite. From these relations it is inferred that fracturing occurred before deposition of freibergite had ceased and was followed by deposition of calcite and chalcopyrite.

DIAGRAM 18. La Negra ore, 217 m. level.

In a few places selective replacement of freibergite by chalcocite was noted following fractures in that mineral and following its contacts with quartz. This represents the beginning of supergene enrichment. As already noted, there has also been a sparse development of oxidized copper minerals, azurite and malachite.

La Negra Mine.—Three specimens from this mine were studied.

A specimen (57034) reported to have come from the 217-meter level shows the paragenetic relations depicted in Diagram 18. It is noteworthy that argentite, which is a minor component, occurs in relations identical with those of galena. Where the two minerals are in contact their boundaries are smoothly curving. The distribution of the argentite bears no relation to galena contacts or cleavages and there are no other evidences of replace-

ment. In porous and slightly weathered parts of this specimen wire silver occurs as an oxidation product of some silver mineral and adjacent pyrite has partially altered to chalcocite. These represent supergene reactions of the ground-water zone.

A specimen (57036) from the 140-meter level exhibits the sequence shown in Diagram 19, a sequence consistent with that

DIAGRAM 19. La Negra ore, 140 m. level.

in the previous specimen. The boundaries between galena, argentite and chalcopyrite are mainly smoothly curving and are not such as to suggest any difference in age. Certainly the argentite is not a replacement of galena for its distribution bears no relation to galena boundaries or cleavages. This diagram should be supplemented, however, by the statement that small vugs in the hand specimen contain well-developed crystals of argentite, pyrargyrite

DIAGRAM 20. La Negra ore, 106 m. level.

and miargyrite. In some vugs rhombic crystals of calcite cap these rich silver minerals. The rich silver minerals are interpreted as late hypogene.

A specimen (57035) from the 106 meter level shows the paragenetic relations represented in Diagram 20. It is noteworthy that among the older minerals the order of deposition differs from that shown in Diagrams 18 and 19. Argentite is a minor associate

of galena occurring in part as inclusions in it and in part side by side with galena in identical relations to other minerals. Although not shown in the polished specimen, miargyrite and calcite were noted in vugs in the hand specimen apparently contemporaneously intergrown with pyrargyrite. All the minerals of this specimen are interpreted as hypogene.

Urista Mine.—A single specimen (57029) from the 190 meter level in this mine was studied. A hypogene association of quartz, pyrite, sphalerite, and galena contains small vugs lined with quartz, upon which lie calcite and native sliver. The native silver occurs in part as "teeth" and wires and is probably an oxidation product of argentite.

Unspecified Mines.—Seven specimens labelled only as coming from the Zacatecas district in the State of Zacatecas show a few noteworthy features.

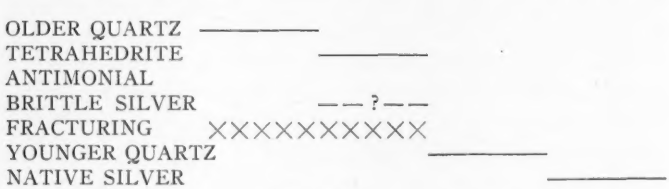


DIAGRAM 21. Unspecified mine, Zacatecas district.

The first specimen (44392) is a highly quartzose ore containing, in vugs, small and unidentifiable remnants of a black, antimonial, brittle silver mineral from which tapering, curling wires of native silver have developed. The mineral sequence is shown Diagram 21.

In another specimen (D, U.S.N.M.) the dominant minerals are quartz and pyrite with sphalerite and galena subordinate. Near vugs, calcite appears with the quartz, and in the vugs pyrargyrite appears as the youngest ore mineral.

In another specimen (I, U.S.N.M.) a layer of miargyrite 1 to 1.5 cm. thick encrusts older ore consisting of quartz, pyrite and sphalerite.

SUMMARY AND CONCLUSIONS.

Mineralogy.—The minerals that were identified in the specimens studied by the writer are listed in Table I, which also shows the genetic conditions under which each mineral appears to have been deposited.

TABLE I.

MINERALS IDENTIFIED IN ORES STUDIED.

	Hypogene			Supergene	
	Early	Intermediate	Late	Zone of Enrichment	Zone of Oxidation
Elements					
Silver				X	X
Sulphides					
Argentite		R	X	X	X
Bornite				R	
Chalcocite				R	
Chalcopyrite	*	X	X		
Covellite				R	
Galena	R	X			
Pyrite	X				
Sphalerite	X				
Sulpho-salts					
Bournonite		†			
Freibergite			X		
Freieslebenite			X		
Miargyrite			X		
Polybasite			X		
Pyrargyrite			X		
Stephanite			X		
Tetrahedrite		X			
Haloids					
Cerargyrite					‡
Fluorite			X		
Oxides					
Hematite				X	
Limonite					X
Quartz	X	X			
Carbonates					
Azurite					X
Calcite	R		X		
Dolomite			X		
Malachite					X

* Mainly as inclusions in sphalerite.
† Noted only in ore from Carmen mine.
‡ Borja mine.
R indicates that the mineral is rare.

In addition to the minerals listed in this table Flores [19] lists the following:

Chalcedony	Native copper
Rhodochrosite	Oxides of copper
Barite	Oxides of manganese
Gypsum	Cerussite
Native gold	Bromyrite

Those of the first column are probably hypogene and those of the second are supergene.

Several features of the mineralogy are noteworthy. A subordinate part of the quartz is pale amethystine. Silver, the dominant precious metal, occurs mainly in argentite, in sulphantimonides of silver, in argentiferous tetrahedrite (freibergite), and subordinately in a lead-bearing sulphantimonide-freieslebenite. Native silver is a subordinate source. Lead is present dominantly in galena but in some of the ore from the Carmen mine the sulphantimonide of lead, bournonite, takes the place of galena. Arsenides are absent and before the blowpipe the sulpho-salts react strongly for antimony but not the slightest arsenic odor is detectable. The absence of marcasite and of stibnite is noteworthy.

No gold or silver tellurides were observed in the specimens studied. According to earlier literature gold is absent or exceedingly rare in most of the veins. In the Australia mine on an extension of one of the Bote veins some of the ore is said by Halse [20] to carry 0.5 to 1.5 ounces of gold.

Paragenetic Sequence.—Many of the details of mineral sequence as displayed in individual ore specimens have been presented in diagrams. Although these exhibit considerable variety, yet a comparison of them shows that certain features are characteristic of the district as a whole.

Three minerals, pyrite, sphalerite and quartz, were the first minerals to be deposited. The order of their deposition, however, shows considerable variability. The commonest order of

[19] Flores, T.: Op. cit., p. 8.

[20] Halse, Edward: Op. cit., p. 78.

deposition is pyrite, sphalerite, quartz, commonly with some overlap. Although all three are generally present, one or even two may be lacking. In a few ores galena was one of the early minerals (Diagram 13) and in some of the ores (Diagram 5) ferruginous calcite crystallized early. Chalcopyrite is represented in this early group only by tiny inclusions in sphalerite which are interpreted as due to unmixing of a solid solution.

Next in sequence in most of the ores were deposited galena and chalcopyrite and in some ores tetrahedrite and rarely argentite, as in La Negra mine where some argentite is contemporaneous with galena (Diagram 20). In a specimen from the Carmen mine, the base metal sulpho-salts, tetrahedrite and bournonite, crystallized contemporaneously (Diagram 14). In Table I the minerals of this group are listed as belonging to the intermediate hypogene group. With the exception of rare argentite, rich silver minerals are absent from this group.

To a still younger group belong most of the minerals that are responsible for the high silver values of the ores including the several sulphantimonides of silver as well as the sulphantimonide of silver and lead-freieslebenite and argentiferous tetrahedrite (freibergite). To this period also belong most of the calcite and dolomite and small amounts of chalcopyrite. With a single exception none of these minerals occur as replacements of older minerals nor is there any other evidence of any hiatus between their deposition and the deposition of the preceding group. Evidence of their youthfulness is found in their conformity to the crystal outlines of the minerals of the previous groups in their tendency to occur in and near vugs in what were obviously the last portions of the ore to crystallize and in their presence in some cases in veinlets cutting the minerals of the previous groups. The younger minerals tend to be more coarsely crystalline than those of the older groups. Only in a specimen from the Guadalupe mine were replacement relations observed. In this ore (57028) freieslebenite occurs mainly as small veinlets traversing galena and always following galena cleavage directions (Fig. 7). These veinlets are of uneven widths with walls that do not " match " and

are typical replacement veinlets. Some of these veinlets are continuous with replacement veinlets of hypogene chalcopyrite and must therefore also be interpreted as hypogene.

Diagram 22 is a composite diagram based upon all of the individual paragenetic diagrams. Obviously many of the details are lost in such a graphic generalization, which represents only the more common relations for the district as a whole. This order is accordant with that given by Lindgren[21] as characteristic of most epithermal deposits.

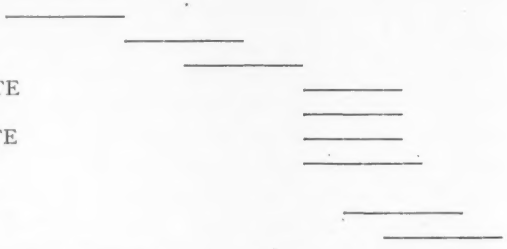


DIAGRAM 22. Composite paragenetic diagram showing the prevailing mineral relations for the district as a whole.

That the hypogene metallic minerals were deposited in the general order of their solubility in pure water as determined by Schürmann and others,[22] the least soluble depositing *last,* rather than first, is sufficient evidence that many other factors besides solubility entered into the physical-chemical picture at the time of ore deposition. This baffling problem has been discussed by Newhouse[23] and need not be reopened here since this paper contributes nothing new to its solution.

In terms of the radicles involved rather than of the minerals the sequence in the hypogene mineralization for the district as a whole may be interpreted as shown in Diagram 23.

[21] Lindgren, Waldemar: Mineral Deposits, 4th edit., p. 122, 1933.

[22] Wells, R. C.: The fractional precipitation of some ore-forming compounds at moderate temperatures. U. S. Geol. Surv. Bull. 609: 45, 1915.

[23] Newhouse, W. H.: The time sequence of hypogene ore mineral deposition. ECON. GEOL., 23: 655–659, 1928.

Quality of Hypogene Mineralizing Solutions.—The paragenetic relations of the minerals of the ores afford no indication of more than a single period of hypogene mineralization. Although quartz was the principal gangue deposited in the early part of the mineralization, ferruginous calcite was also an early deposit in the Mala Noche mine (Diagram 5) and calcite or dolomite or both are common companions of the rich silver minerals deposited late in the mineralization. In the Carniceria mine, for

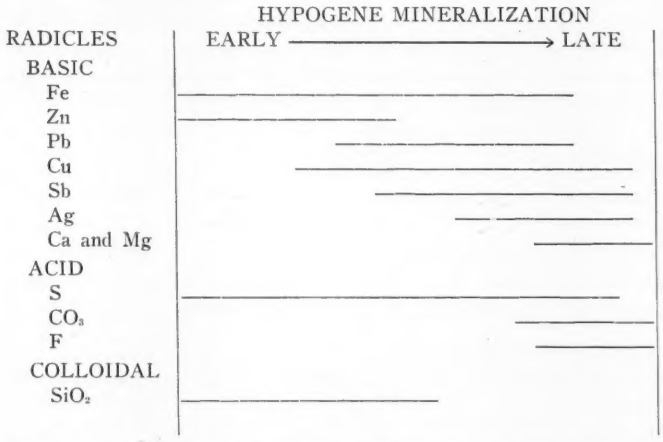


DIAGRAM 23. Hypogene paragenetic sequence for the district as a whole in terms of radicles.

example, argentite and polybasite are in places intercrystallized with calcite in vugs, and elsewhere argentite caps calcite crystals that show no evidences of corrosion. Because of the presence of these carbonates it is a reasonable inference that the ore depositing solutions were certainly not acid in the later stages of hypogene mineralization and perhaps not acid at any stage of the process.

Supergene Mineralization.—Although most of the ores studied carried hypogene copper in moderate amounts in chalcopyrite and less commonly in tetrahedrite and polybasite, copper sulphides due to supergene processes are only sparsely developed in a few speci-

mens in which small amounts of chalcocite, bornite and covellite were noted as replacements of hypogene minerals (Diagram 3).

Native silver in the Zacatecas ores is mostly an oxidation product, but in a single specimen from the Mala Noche mine dendritic growths of crystalline silver were deposited on crystals of pyrite and of calcite. Thin coatings of argentite also occur on these same minerals. The silver does not seem to be an alteration of argentite but both minerals seem to be direct and nearly simultaneous deposits from solution. It is probable that this silver and the accompanying argentite were deposited by supergene solutions in the ground-water zone.

In many of the specimens studied native silver occurs in vugs or along open fractures as tapering, curling "teeth." Such silver is a product of the oxidation of argentite or of sulpho-salts of silver, for in many instances the "teeth" still rest on a base of argentite or of pyrargyrite. As is well-known, similar "teeth" can be observed to "grow" out of argentite when a fragment of the latter is rapidly oxidized by heating in contact with air on an electric hot plate. In a single specimen from the Borja mine cerargyrite was observed as an oxidation product of argentite.

UNIVERSITY OF CHICAGO,
January 6, 1941.

ZONING AND DISTRICT VARIATIONS OF THE MINOR ELEMENTS IN PYRITE OF CANADIAN GOLD DEPOSITS.

P. E. AUGER.

ABSTRACT.

Samples of pyrite from a number of gold and gold-copper mines were analyzed spectrographically for minor elements.

It was found that: (1) Within one mine, one district or even one region, some minor constituents show a very consistent supremacy over other elements; (2) The type of ore deposit or the temperature of deposition has affected the nature of the accessory elements; (3) The nature of the wall-rock has no apparent effect on the distribution of the minor elements in pyrite; (4) Gold in the sulphides has a very erratic distribution. It is considered that most of the elements found in pyrite except gold are part of the pyrite crystal structure.

A systematic analysis was made of hundreds of sulphide samples from the Hollinger, Noranda and Siscoe Mines. The samples taken at regular level intervals in the mines showed that: (1) There is a systematic variation with depth in the quantities of minor elements; (2) The type of variation does not agree with the usual zonal precipitation of minerals; (3) The vein type of deposits gives more erratic values for the minor elements than does the massive sulphide type of deposits.

INTRODUCTION.

THE spectrograph has a wide field of utility for the solution of problems in various branches of economic geology. This method is now extensively used for technical control in industry and is a useful tool to investigate practical as well as scientific problems in connection with the origin of ore deposits and field exploration.

The present work has been done in order to determine the relationships between the amount and kind of minor elements in sulphides, the province in which the ore deposits occur and the geological or structural features with which the deposits are associated. The series of specimens, mostly pyrite and pyrrhotite, which were analyzed come from various mines of the pre-Cam-

brian Shield and several other regions like the Mother Lode in California and some epithermal deposits of Mexico.

The author wishes to express his gratitude for the helpful co-operation of Dr. W. H. Newhouse who suggested the program and directed the research. Thanks are also due to R. F. Jarrell who assisted in the use of the spectrograph and carried on a complete series of check determinations on the Hollinger and Siscoe samples. The Quebec Bureau of Mines is to be thanked for granting financial help in order to facilitate the completion of this research program.

PROCEDURE.

The analyses were made in the spectrographic laboratory of the geology department at the Massachusetts Institute of Technology. The apparatus used for all the determinations is a 21 foot 30,000 line grating spectrograph in Wadsworth mount which covers a range of 3500 Å between 2500 Å and 6000 Å. The part of the spectrum used mostly in the course of this program is from 2810 Å to 4625 Å. This range was selected after several trials over the whole range and it was found that all the rare elements detected in the sulphides had their most sensitive lines in this portion of the spectrum. The material for most determinations was collected by the author in the various mines of Quebec and Ontario. Many other samples were also secured through the generosity of the management of different mining companies. Great care was taken to obtain the exact location of the specimens and to prevent contamination during the sampling.

The spectrographic determinations were recorded on "Eastman Process Nitrate" films 4 inches wide and 29.5 inches long, from excitation by the carbon arc method. Numerous sources of errors may affect the results and care was taken to eliminate these as much as possible. The most common source of error is a non-uniformity of the samples and the presence of impurities mechanically included within the crystals. For this reason, in selecting the specimens, we tried to obtain small, perfect, inclusion-free, crystals of pyrite 1 mm. and less in diameter. Each sample

was composed of dozens of these crystals, that were selected under the binocular and the powder was examined and cleaned at different stages of the crushing. In doubtful cases, polished sections of the original sample were examined.

A general study was first made of the minor elements in the pyrite from different districts. This series was studied in a semi-quantitative way only. The intensity of the lines was estimated with the eye according to an arbitrary scale expressed by successive numbers from 0 (absent) to 7 (intense).

After this preliminary study a photo-electro microphotometer was used to obtain a higher precision in measuring the line intensities. In most cases a comparison of the relative quantities of minor elements in the pyrite was sufficient to show the variations from one sample to another. This was determined by means of the logarithmic step sector and the intensity of the lines was established with the microphotometer and expressed in Δ log. I which is an expression of corrected intensity of the lines. When it was found convenient, an absolute quantity scale was determined by comparison with spectra of standard powders and substituted to the Δ log. I coordinate. The standard powders were prepared by mixing definite quantities of the rare elements in the form of oxides to a base that was pyrite in the present case. It was found that the form in which the rare element is in the synthetic powder affects the slope of the quantity curve. The sulphides of the elements would have been best in the present case, but as they are generally impure, we had to use the oxides, after having tried the sulphates, which proved impractical on account of hygroscopic properties. Therefore, we cannot consider these absolute quantities as absolutely accurate. Each quantitative result represents the average of two separate analyses. Examination of the data shows that the majority of the averages of Δ log. I are accurate to $\pm .02$ ($\pm 5\%$) in the case of Ni, and $\pm .05$ ($\pm 12\%$) for the other elements. Occasional averages may be uncertain by as much as $\pm .10$ ($\pm 25\%$). The Ni results are uniform throughout. Of the other elements, Mn and Ti are subject to occasional wide variations possibly due to in-

clusions in the samples or contamination. Ba, Si and Ag are also subject to considerable fluctuation due to possible differences in arc conditions from one burning to another.

TABLE 1.

Elements.	Most sensitive line.	Sensitivity for pure element.	Checkline.	Sensitivity for pure element.
Ag	3280.683	2000R	3382.891	1000R
As	2780.197	75R	2860.452	50r
Au	3122.781	500h		
Be	3321.343	1000r	3321.086	100
Bi	3067.716	3000hr	3897.975	500R
Co	3453.505	3000R	3405.120	2000R
Cr	4254.346	5000R	4274.803	4000R
Cu	3247.540	5000R	3273.962	3000R
In	4511.323	5000R	3256.090	1500R
Mn	4030.755	500r	4034.490	250r
Pb	4057.820	2000R	3639.580	300
Sc	3911.810	150	4246.829	80
Sn	3175.019	500	3034.121	200
Sr	4607.331	1000R		
Ti	3372.800	80	3349.406	100
V	3183.982	500R	4379.283	200R
W	4294.614	50	4008.753	45
Yt	4374.935	150	3600.734	100
Zn	3345.020	800	3345.572	500
Zr	3391.975	300	3496.210	100

Meaning of symbols:
R: wide self-reversal,
r: narrow self-reversal,
h: hazy, diffuse, nebulous.

Table 1 gives a list of the principal lines utilized for the spectrographic determinations in a semi-quantitative way, by eye estimation of line intensity.

Possible State of the Minor Elements in Pyrite.—The minor elements may be housed in the pyrite in a number of ways: as admixed solid inclusions, fluid inclusions, exsolution products and solid solution; the latter may be subdivided into substitutional, interstitial and " omission " types of solid solution.

A careful selection of the crystals, a continuous check with the microscope during the preparation of the samples, frequent examination of polished sections in doubtful cases and especially the consistency of the spectrographic results on the same samples ruled out quite definitely the possibility of having the accessories

in the form of inclusions. Since most of the minor constituents of pyrite are uniformly distributed in it, this indicates that these elements form an integral part of the crystal structure.

The question now arises as to the manner in which the minor elements are housed in the crystal structure of pyrite or of the other sulphides in which they are found. Table 2 lists the elements found in the pyrite and pyrrhotite samples, together with other pertinent data.[1]

TABLE 2.

Elements.	Atomic number.	Valence.	Atomic radii.	Atomic weight.
Mg	12	2	1.595	24.32
Al	13	3	1.48	26.97
Si	14	4	1.172	28.06
S	16	2 4 6	1.06	32.06
Ca	20	2	1.97	40.07
Sc	21	3	—	45.10
Ti	22	3 4	1.45	47.90
V	23	3 5	1.313	50.95
Cr	24	2 3 6	1.246	52.01
Mn	25	2 4 6 7	1.238	55.84
Co	27	2 3	1.25	58.94
Ni	28	2 3	1.243	58.69
Cu	29	1 2	1.275	63.57
Zn	30	2	1.329	65.38
Sr	38	2	2.14	87.63
Y	39	3	1.79	88.93
Mo	42	3 4 6	1.36	96.00
Ag	47	1	1.441	107.88
Cd	48	2	1.486	112.41
In	49	3	1.62	114.8
Sn	50	2 4	1.40	118.70
Ba	56	2	2.17	137.36
Au	79	1 3	1.439	197.20
Pb	82	2 4	1.746	207.21
Bi	83	3 5	1.55	209.00

Table 2 shows that the elements fall in groups within the atomic number sequence. The atomic radii of these elements are closely related except Ca, Ba and Sr which belong to the second group of the periodic table and have larger atomic radii. The

[1] Stillwell, C. W.: Crystal Chemistry, pp. 417–419, 1938. (Atomic weight and valence columns were added by the writer.)

elements of the second group of Table 2 are the most common in the samples analyzed and have atomic dimensions that would permit them to be substituted for iron in the pyrite structure. The most closely related are: Fe, Co, Ni and Mn which are present in almost all of the samples studied and bear close relationships in their atomic properties. These elements are also closely related to one another by their chemical properties.

To summarize the above discussion, it may be said that the uniform distribution of the elements in the samples, the commensurable atomic radii, atomic weights, electronic configuration and chemical properties leads to the idea that the most common minor elements and especially those of the Fe, Ni, Co group are included in the pyrite structure as solid solution of the substitutional type. However, this does not exclude the possibility that elements of smaller atomic radius may be present as interstitial solid solution.

Possible Effect of Crystal Habit on the Distribution of the Minor Elements in Pyrite.—Another factor that might affect the content of minor elements in pyrite is the crystal form of the pyrite. It is known that impurities are absorbed selectively by the various faces of a crystal.[2] It is, therefore, possible that when a crystal assumes a different habit, the impurities that are generally absorbed by the predominant faces of this habit should be present in larger quantity. In the present case, nearly all of the samples had the cubic form. Only four were found to possess the octahedral habit. These four specimens had only one thing in common—a very low content of manganese. It so happens that these specimens are from the mesothermal types of deposits and as will be shown below, this low content of manganese is to be expected.

RESULTS.

One hundred and twenty-four samples were analyzed from mines in various districts of Canada. The districts within the pre-Cambrian Shield which were studied will be considered first and then a comparison will be made with other districts outside of the Shield.

[2] Frondell, Clifford: Personal communication, 1939.

The most striking fact observed is that within the pre-Cambrian Shield the minor elements in pyrite are very similar in quantity and quality. Most prominent is the Fe-Co-Ni group, which appears in almost every sample in appreciable quantities. It is interesting to compare the relative quantity of these elements from one district or from one mine to that from others. As mentioned above, the figures obtained do not permit a determination of absolute quantities among the minor elements. However, the apparent supremacy of one over the other is significant because the same lines were used consistently for each individual minor constituent.

Within one district or one mine, the apparent supremacy of one element over another is very consistent. In Tables 3 to 5 several elements in pyrite from various districts are compared.

TABLE 3.

Ti *vs.* Cr.		Ti *vs.* Cr.	
Central Manitoba	Ti < Cr	Gunnar, Ont.	Ti > Cr
Perron, Que.	Ti < Cr	Kenora, Ont.	Ti > Cr
Michipicoten, Ont.	Ti < Cr	Howey, Ont.	Ti > Cr
Porcupine District, Ont.	Ti < Cr	L. Long Lac, Ont.	Ti > Cr
Cadillac District, Que.	Ti < Cr	Hollinger, Ont.	Ti > Cr
Francoeur, Que.	Ti < Cr	Lake Shore, Ont.	Ti > Cr
Montezuma, Calif.	Ti < Cr	Malartic, Que.	Ti > Cr
S. Québec, Que.	Ti < Cr	North Star, Calif.	Ti > Cr
		El Oro, Mex.	Ti > Cr
		Aldermac, Que.	Ti > Cr
		Noranda, Que.	Ti > Cr

TABLE 4.

Cr *vs.* Mn.		Cr *vs.* Mn.	
Cadillac, Que.	Cr < Mn	Lake Shore, Ont.	Cr = Mn
Central Manitoba	Cr < Mn	Sullivan, Que.	Cr = Mn
Gunnar, Manitoba	Cr < Mn	L. Long Lac, Ont.	Cr > Mn
Kenora, Ont.	Cr < Mn	Michipicoten, Ont.	Cr > Mn
Howey, Ont.	Cr < Mn	Perron, Que.	Cr > Mn
Porcupine and Hollinger, Ont.	Cr < Mn	Cournor, Que.	Cr > Mn
Aldermac, Que.	Cr < Mn	Malartic, Que.	Cr > Mn
Noranda, Que.*	Cr < Mn		

TABLE 5.

Co *vs.* Ni.		Co *vs.* Ni.	
Hollinger, Ont.	Co < Ni	Kenora, Ont.	Co > Ni
S. Ontario, Ont.	Co < Ni	Michipicoten, Ont.	Co > Ni
Montezuma, Calif.	Co < Ni	S. Ontario, Ont.	Co > Ni
		North Star, Calif.	Co > Ni
		Aldermac, Que.	Co > Ni

* The results from Noranda were studied under different conditions and cannot be included in these tables unless one element is absent with respect to another.

A similar type of comparison could be made for silver, lead and zinc in the same pyrite samples. The silver line intensities exceed by far the two others in ores of most camps, but at Hollinger, the relative ratios vary with depth. The mines of lower temperature type, like those of California and Mexico, show an equal intensity for the lines of the three elements, or a much larger intensity for lead, as at El Oro, Mexico.

It seems evident from the above tabulation that within one mine there is a consistent ratio between the intensity of the lines representing the minor elements in pyrite. For some elements the ratio seems to be consistent for an entire district when the samples were from similar types of deposits. A good example of this is the Cr:Mn intensity ratio for the Malartic-Bourlamaque district, Quebec. Here chromium is apparently either equal to or greater than manganese but never smaller. On a larger scale, the lead, zinc and silver of the pyrite from Californian and Mexican mines predominate over all the other minor elements present.

Much rarer elements may be considered when comparing the various districts of the Canadian Shield. For instance, cadmium and columbium are present at Hollinger only; yttrium was found at Hollinger, Aldermac and Sullivan; lead is present at the Sladen Malartic and Hollinger, and as mentioned above, also in the pyrite from the Californian and Mexican mines. Molybdenum was detected at the Francoeur, Lake Shore and the Sladen Malartic gold mines only.

The total absence of one or more elements in some ore deposits is also worth considering. Noranda, for instance, does not contain any molybdenum in its sulphides. More than one hundred specimens from this mine were analyzed without revealing even a trace of the element. Eleven samples of pyrite from the Aldermac, which belongs to the same type of deposit and the same district as the Noranda, were found to be lacking in this element. The same may be said of chromium which is almost non-existent at Noranda, very minor at Aldermac and completely absent in the pyrite from the Amulet and Eustis mines. This result is cor-

roborated by Newhouse [3] who did not find a trace of chromium in a series of determinations on pyrite from different levels at the Eustis mine.

Finally there are two elements, tin and indium that are present in the sulphides, especially pyrrhotite and chalcopyrite, of Noranda and were not found in any of the other deposits examined.

Minor Elements in Pyrite from Various Types of Deposits inside and outside of the Canadian Shield.—A definite conclusion that may be drawn from the results obtained is that the type of ore deposit has a definite bearing on the nature and proportions of the minor elements present in the pyrite. The Noranda, Aldermac, Amulet and Eustis mines, Quebec, which are all of the massive sulphide type, show a definite relationship regarding their minor elements. The distribution of the accessories in these ores is also different from that of the gold-quartz vein type considered above. A brief tabulation will bring out the differences between the two types of deposits.

	Massive sulphide deposits.	Vein type deposits.
Sn	present at Noranda and Eustis	absent
In	present at Noranda	absent
Cr	very minor or absent	large
Mo	absent	frequent

These two types of deposits may also be compared with a third group, which is of a lower temperature type and is located outside of the Canadian Shield. Representative of this group are the Argonaut, Montezuma and the North Star mines of California and the El Oro mine, in Mexico.

California and Mexico gold-quartz deposits.	pre-Cambrian shield gold-quartz deposits.
Cr: absent (except for traces at Argonaut and Montezuma)	large
Mn: absent	large
Ni: absent or in traces only	large
Co: absent	large
Pb: large	low or absent
Zn: large	low or absent
Ag: large	low or absent

The most striking difference between the minor elements of the pyrite of these two geographical provinces is in the ratio Cr, Mn,

[3] Newhouse, W. H.: Personal communication, 1939.

Co, Ni: Pb, Zn, Ag. The presence of relatively large quantities of these lower temperature elements in the pyrite of the lower temperature types of mines seems to corroborate perfectly the classification of ore deposits made by Lindgren and confirmed by many other workers.[4] The three California mines mentioned above are classified as mesothermal ore deposits and the El Oro of Mexico belongs to the epithermal class.[5] It seems evident that the distribution of the minor elements in the pyrite is a reflection of the type of mineralization and that they also serve as indicators of the relative conditions under which the pyrite deposition took place.

Another interesting point to note in connection with the previous observations is that the three elements Pb, Zn, Ag, and even gold, were found only in the pyrite connected with ore deposits containing at least one of these elements in commercial quantity. All the pyrite samples from the pure sulphide deposits like the Eustis, Clark, Billings and McIlwraith do not show any of these elements, except possibly a trace of silver in a few specimens from the Eustis and one from the Mouton Hill.

Effect of Wall Rocks on the Distribution of Minor Elements.— The results so far obtained indicate that the nature of the country rock, the gangue and the type of wall rock do not have any bearing on the distribution in pyrite of the minor elements given in Table 1. For example, a comparison may be made of several extreme cases in which the wall rock is of a different character.[6]

A comparison of the minor elements in the pyrite from these mines shows that there is no essential difference that could possibly be related to the nature of the wall rock. At most properties

[4] Lindgren, W.: Mineral Deposits, pp. 203–212, 1933.

[5] Lindgren, W.: *op. cit.*, pp. 481, 547, 548, 593, 594.

[6] In these mines the samples came from sections containing one of the types of rocks mentioned.

Granodiorite, granite, rhyolite and pegmatite wall rock	Basic lava, graywacke, gabbro, diabase, tuff and breccia wall rock.
Sullivan, Que.	Michipicoten, Que.
Perron, Que.	Argonaut, Calif.
Howey, Ont.	Francoeur, Que.
Canadian Malartic, Que.	East Malartic, Que.
	Central Manitoba,

a great variety of rocks outcrop at the surface and this heterogeneity must also exist at depth. If we assume that the solutions have travelled for a long distance, they must have come in contact with several of these different rocks and may have, in part or wholly, acquired from them the random quantities of the minor elements observed in our samples. Another explanation, the one preferred by the writer, is that in this type of gold-quartz deposit the total composition of the pyrite is mainly dependent on the nature of the solutions. If such is true, the original composition of the solutions is the most important factor and the addition of elements from the wall rock is negligible.

Distribution of Gold in Pyrite.—It must be kept in mind that these separate spectrographic tests were each made on approximately 15 milligrams of pyrite very carefully selected under the binocular. Thus a different kind of information is obtained than would be by fire assaying on charges of many grams of ore.

Gold is not very sensitive to spectrographic analysis. Tests of some pyrite samples however gave heavy gold lines in their spectrum. Additional tests run on these specimens failed to show consistent results, but the line intensity for the other elements present was consistent for different analyses of the same sample. This suggests strongly that the gold, whenever present, is unevenly distributed in the pyrite crystals and shows up in the spectrum only when one happens to pick up a small particle of free gold. Hegemann and Rost [7] noticed that the distribution of gold in pyrite was very irregular and they attempted to work out a method to obtain a representative sample. In the present study all of the positive tests came from pyrite in the high grade section of the ore deposits where visible gold was present. The reverse however is not true, namely, that all pyrite samples from gold-rich ore did not give positive tests. Of twenty-eight pyrite samples labelled "high grade," gold was spectrographically determined to be present in only some of the separate tests or "runs" on two of the samples. The results on these two varied from zero to high, in this element.

[7] Hegemann Fr. and Rost Fr.: Uber die quantitative spectrographisch Bestimung des Gold in Pyrite. Angew Min. B. 1, Heft. 2, pp. 97–102, 1938.

The grade of ore in the mine, where there was no visible gold, did not seem to affect the spectrographic amount of this element in the pyrite. The mesothermal deposits of Montezuma, North Star, and Argonaut, California, showed an outstandingly large and rather consistent gold content in their pyrite. It is possible that the gold is more uniformly distributed in this type of pyrite, but it must be remembered that these mines contain rich pockets of native gold.[8] On the other hand the El Oro mine, which is of a still lower temperature type, contains gold but, according to Lindgren, none of it can be seen in the mine, and the spectrographic analysis of this ore did not reveal any gold in the pyrite.

The above mentioned observations lead to the belief that gold is irregularly distributed in the pyrite and does not take part in the structure of the crystal as solid solution. On the contrary, it appears to be present in the native or combined form as isolated units or narrow veinlets due to later replacement or fracture filling within the pyrite crystals. A logical deduction from the above statement is that the gold was not precipitated at the same time as the pyrite.

VARIATION OF MINOR ELEMENTS WITH DEPTH WITHIN SINGLE ORE DEPOSITS.

The samples for this study came from three mines, namely, the Hollinger, Noranda, and Siscoe mines. The Hollinger samples were collected by different workers and little attention was given to their exact location in a vein, other than their depth. A number come from the center of the veins and others from the edges. No definite vein system was followed and depth was the only variable factor that was considered.

The samples obtained at the Noranda mine were selected by the writer from the two "H" orebodies and most of them contained both pyrite and pyrrhotite. These two minerals were separated and analyzed, as were also chalcopyrite and magnetite when available.

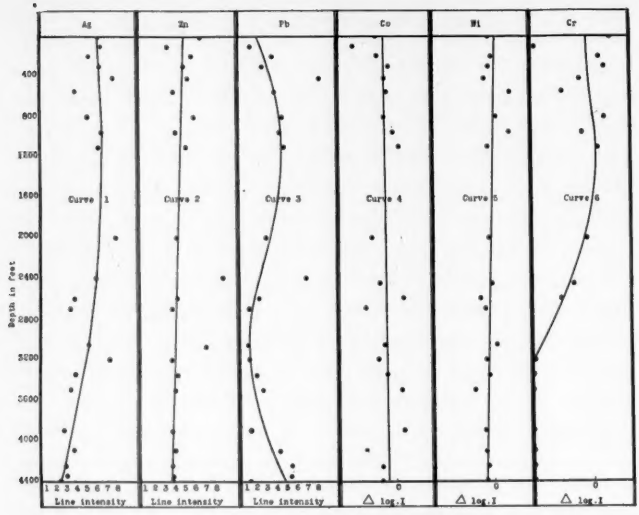
[8] Lindgren, W.: *op. cit.*, p. 54.

All of the Siscoe samples were collected by the author from the following three ore zones. "K," "Main" and "Siscoe."

Minor Elements in the Hollinger Pyrite.

All of the samples from this mine were run four times, twice semi-quantitatively by the author and twice quantitatively by R. F. Jarrell. The results of the two operators checked sufficiently to give similar graphs in spite of the different methods employed. The samples represent a range from the surface to a depth of 4400 feet, except for a section of 900 feet (between the 1100 and the 2000-foot levels), from which no suitable sample could be secured. Several samples from each level were analyzed with the spectrograph and each determination was repeated four times. The results were averaged for each level and plotted in Δ log I values on the horizontal coordinate against the depth in feet, to obtain the graphs represented on Fig. 1. The curves 1, 3 and 6 representing the variation with depth of Ag, Pb and Cr in the Hollinger pyrite show a much greater variation than the other curves. The scattering of the points is also greater in these curves and this is especially true for the determinations on titanium and barium, which showed such a wide range of variation that we did not venture to draw a curve between the points. In a general way, it was observed that the specimens from vein material give rather irregular results, due no doubt to the fact that the samples were collected from different parts of the veins and even from different veins on the various levels.

The trend of variation in silver content with depth shows a rather uniform quantity in the samples from the surface to a depth of approximately 2400 feet. From this point, the silver content decreases uniformly with depth to a minimum at 4400 feet. The zinc content shows a gradual but regular decrease with depth and does not seem to have an appreciable maximum at any point in the mine. Lead in the Hollinger pyrite has an appreciable range of variation. From the surface the quantity of this element increases gradually to a maximum at about the 1000-foot level. From this point down to 2400 feet, few data are available,



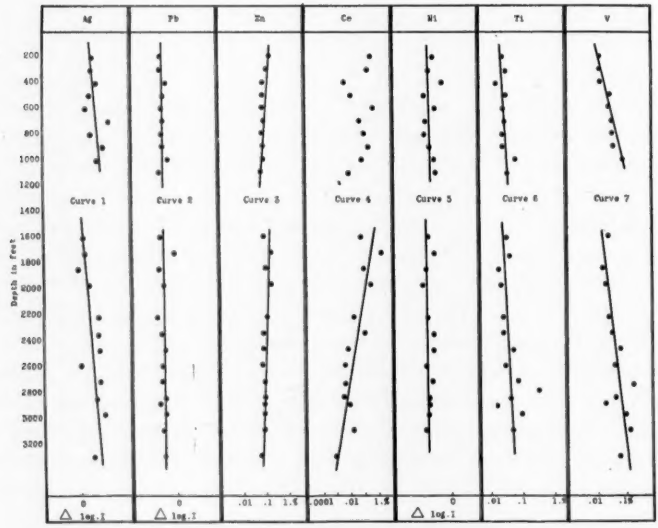


FIG. 1 (Upper). Variation of elements with depth in pyrite at Hollinger, Ont.

FIG. 2 (Lower). Variation of elements with depth in pyrite at Noranda, Que.

but a decrease is clearly indicated with a minimum close to the 3000-foot level. Below this point the lead content seems to increase slightly to the lowest level considered here.

Curves 4, 5 and 6 of Fig. 1 show the behavior of cobalt, nickel and chromium in pyrite samples. Chromium decreases considerably with depth and is completely lacking below the 3200-foot level. Nickel decreases slightly and cobalt seems to increase gradually with depth. In the last case, however, the points are quite scattered and it is difficult to establish the exact trend of the curve. The widely scattered points of Ti and Ba have been mentioned and it may be added that this irregularity is more extensive above the 3200-foot level. Strontium does not show any variation from the top to the bottom of the mine.

Discussion of the Results.—The variations observed in the graphs are caused by local increase or decrease of some elements, which probably reflect changes in the conditions of equilibrium of the solution from which the pyrite was deposited. Temperature variation within a single mineralization like the Hollinger may be an important factor affecting the variation of the minor elements. At depth where the temperature was higher, conditions favorable to the deposition of elements that are deposited at lower temperature, such as silver, lead and zinc, or minerals containing large percentages of these elements, were less effective.[9] Nearer the surface, the temperature decreased, a state of unstable equilibrium was reached, and the minor elements began to precipitate along with the pyrite. This might be the reason why the present determinations indicate a gradual increase of lead, zinc, silver, chromium and others, with decreasing depth. A close inspection of the curves, however, does not support this. Consideration of the maxima with respect to mine depth discloses that silver has a maximum between the 1000 and 2400-foot levels and that lead has a maximum at about 1200 feet and a minimum at 3000 feet. Zinc and most of the other elements, especially chromium, show an increase from the bottom to the top of the mine. This would suggest that, for the range of depth studied, the ideal con-

[9] Lindgren, W.: *op. cit.*, p. 119.

ditions for the precipitation of lead were reached at the point indicated by the maximum. The same applies to silver whose ideal conditions of precipitation would cover a greater depth range. All of the other elements, except possibly cobalt, gradually increase toward the surface, as if their maximum were above this point, which may have been far below the original surface at the time of deposition.

Such results seem to oppose the well accepted theory of successive mineral deposition. Emmons,[10] Lindgren,[11] Newhouse,[12] and numerous other workers have proved the following succession of elements in deposits of primary origin: Fe, Co, Ni, W, Sn, Mo, Bi, Zn, Cu, Pb, Ag, Au. The last elements in the series would be the last ones to appear, and if we assume that the minor elements in pyrite are primary and obey the same laws as those considered by these different workers, the maximum quantity of silver in pyrite should be closer to the surface than that of lead. For the same reason, other elements like zinc, nickel, chromium and titanium should have their maxima at the very bottom of the mine or even below and show a gradual decrease toward the surface. It must be remembered, however, that the succession of deposition mentioned above was worked out for minerals only, whereas this work is concerned with small percentages of elements that are probably part of the host pyrite structure and may obey different physico-chemical laws.

Minor Elements in Noranda Sulphides.

Three complete sets of spectrographic analyses were made on the samples from this mine. One for the minor elements in pyrite, one for those in pyrrhotite and a third incomplete set for chalcopyrite. The points shown on the curves of Figs. 2–4 are an average of the results from at least three samples collected on each level. The vertical scale represents the depth in feet. The

[10] Emmons, W. H.: Primary downward changes in ore deposits. Trans. A. I. M. E., 70: 964–992, 1924.

[11] Lindgren, W.: Magmas, dikes and veins. Trans. A. I. M. E., 74: 88, 1926.

[12] Newhouse, W. H.: Hypogene ore mineral deposition. ECON. GEOL., 23: 649, 1928.

upper section from 200 feet to 1100 feet includes the "Upper H" and the lower part from 1600 to 3300 feet, the "Lower H" orebody. The horizontal scale represents the quantity of minor elements present in the sample. It was found impossible to determine the absolute quantity of some of the elements such as silver and nickel on account of the quantity of these elements in the standard mixture base. In such a case the horizontal coordinate represents the Δ log I.

Minor Elements in Pyrite.—Silver shows a definite increase from the top to the bottom of each orebody. The rate of increase and the maxima are about the same in both cases but the minima are quite different in the sense that the amount of this element in pyrite is less at the top of the "Lower H" than at the top of the "Upper H" orebody. It is interesting to note the sudden change in relative amounts of silver from the lowest point of the "Upper H" to the highest of the "Lower H" orebody.

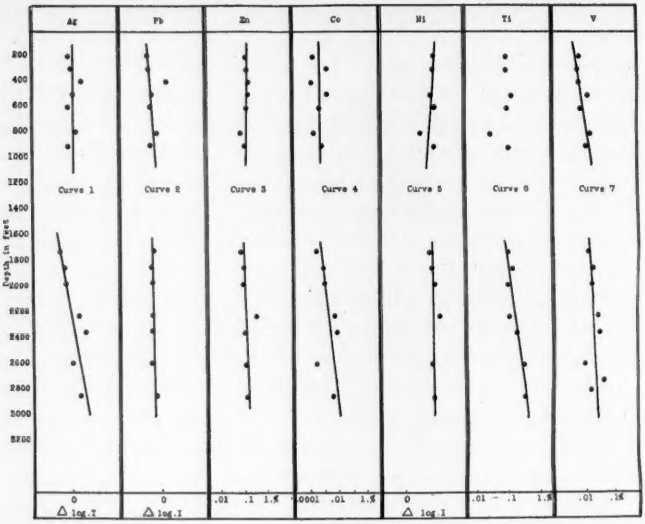
Vanadium is another outstanding example of a similar individual variation in pyrite, with a maximum at the bottom and a minimum at the top of each orebody.

Titanium shows a similar behavior on a smaller scale, the total range of variation is from .03 to .09 per cent whereas the vanadium varies from .01 at the top to .2 per cent at the bottom of the orebodies. Over the total vertical extension of the mine, the general content of lead and nickel in pyrite is practically constant and continuous in the two orebodies.

Zinc on the other hand decreases slightly in quantity with depth in each orebody, although the range of variation is small (from .2 to .07 per cent). The content of cobalt is generally high but slightly erratic in pyrite from the "Upper H" orebody. In the "Lower H" it decreases from .5 at the top to .001 per cent at the bottom. This is the greatest range of variation that has been observed in the course of this work.

Minor Elements in Pyrrhotite.—Fewer samples of pyrrhotite were available and for this reason all the levels are not represented in the graphs of Fig. 3.

The trend of variation is similar in pyrite and pyrrhotite for



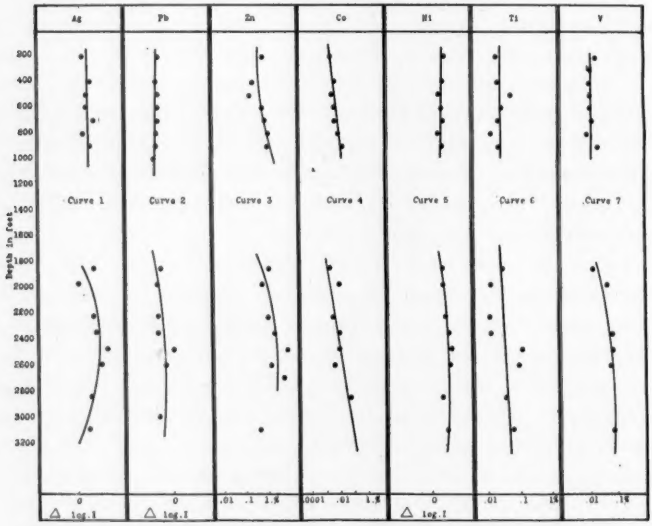


FIG. 3 (Upper). Variation of elements with depth in pyrrhotite at Noranda, Que.

FIG. 4 (Lower). Variation of elements with depth in chalcopyrite at Noranda, Que.

zinc, vanadium, titanium and possibly nickel. Silver in pyrrhotite does not show any increase with depth in the "Upper H" orebody, but does in the "Lower H." Lead, which is very constant in pyrite, increases slightly with depth in the "Upper H" orebody. Cobalt, which is low and uniform in the "Upper H" orebody, increases from .0005 to .01 per cent in pyrrhotite from top to bottom in the "Lower H" orebody. When comparing the behavior of the minor elements in pyrite and pyrrhotite, it is noted that the trend of variation is very close in the two minerals for most elements except cobalt, whose curve for pyrrhotite is reverse to that established for pyrite. The total quantity of each element in both pyrite and pyrrhotite is another interesting point to consider. A superposition of Figs. 2 and 3 shows that vanadium is more abundant in pyrite than in pyrrhotite. The silver and cobalt content is also greater in pyrite in the upper part of the mine but the difference gradually decreases with depth until near the 2800 level where the relative amounts are equal in pyrite and pyrrhotite. All of the other elements considered here show a larger content in pyrrhotite than in pyrite. Nickel and titanium are much more abundant in the former mineral, and the difference, which is of the order of .05 per cent, is rather consistent with depth.

Minor Elements in Chalcopyrite.—Only a limited number of specimens contained enough chalcopyrite to permit a spectrographic determination of the minor elements in this mineral. Fig. 4 shows that silver behaves in the same manner as in pyrrhotite except for a slight decrease near the bottom of the "Lower H" orebody. Lead decreases very slightly with depth in the "Upper H" and increases in the "Lower H" orebody to a possible maximum at 2500 feet, which depth presents a similar maximum for silver and zinc. The latter element shows a greater variation than in pyrite and pyrrhotite. It increases with depth, especially in the "Upper H" orebody. Cobalt increases toward the bottom of each orebody, nickel is constant and very high as in pyrrhotite, and titanium is low and quite erratic.

Discussion of Results Obtained.—The discontinuity in trend of the curves for most minor elements from the bottom of the "Upper H" to the top of the "Lower H" orebody at the Noranda mine seems to indicate quite definitely that the temperature of deposition commonly related to the distance from the surface at the time of deposition did not regulate the precipitation of the minor elements in the sulphides of both orebodies, considered as one continuous unit. Silver and vanadium in pyrite illustrate this point very well. However, the relation of temperature to the surface may be considered as an important factor if the two orebodies are looked upon as two separate units.

The behavior of Ni and Co is most interesting. These two elements are closely associated, yet they show different types of variation with depth in pyrite and pyrrhotite. In all samples, nickel is present in larger quantity in pyrrhotite than in pyrite. Cobalt, on the other hand, is generally present in lesser amount in pyrrhotite except at the 2800-foot level in the "Lower H" orebody where it equals the cobalt content of pyrite after a gradual increase all through the "Lower H" orebody. Such behavior seems odd in view of the close relation of these two elements. It has been suggested that under certain physical conditions the crystal structure of pyrrhotite might undergo changes that facilitate the housing of cobalt.

Another point worth considering is that in the "Lower H" orebody silver increases in depth in both pyrite and pyrrhotite but at different rates, so that it is practically equal in these two minerals around the 2800-foot level. This is also the level at which the cobalt content of pyrite equals that of pyrrhotite. It seems that at this depth the conditions were such that both these elements precipitated at an equal rate in pyrite and pyrrhotite.

Minor Elements in the Siscoe Pyrite.

The most complete set of specimens collected in this mine by the author was from the "K" zone which is a strong shear zone along the contact between the granodiorite and the Keewatin greenstone. The other sets are from the "Main" and "Siscoe"

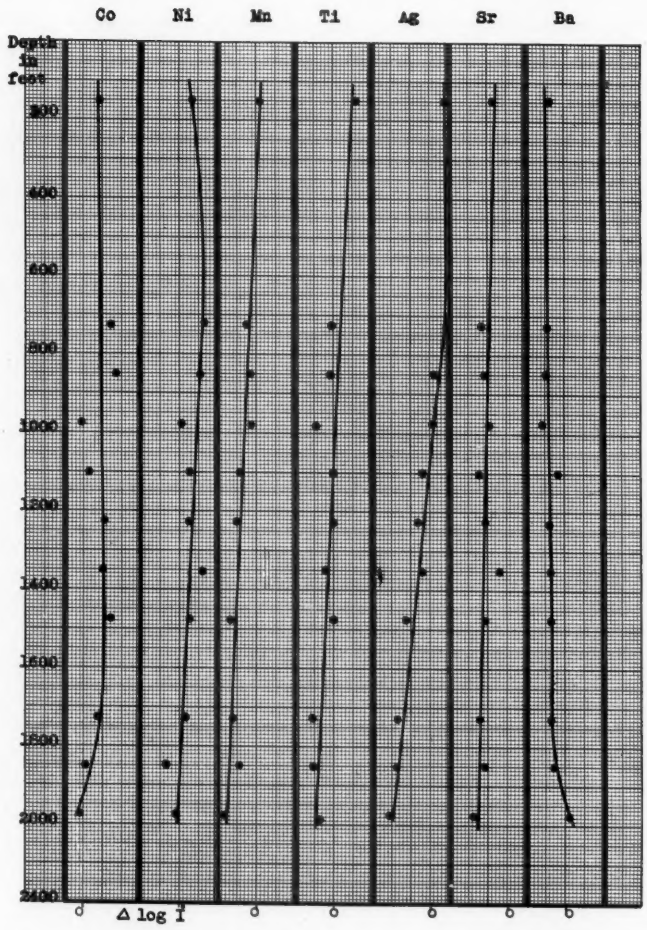


FIG. 5. Variation of elements with depth in pyrite of the "K" zone at the Siscoe Gold Mine, Que.

veins, which are located in large tension fractures in the granodiorite, believed to be due to the shearing of the "K" zone. These veins contain very little sulphide and we could not obtain samples from each level examined.

Fig. 5 shows the type of variation with depth observed in the "K" zone of the Siscoe gold mine. The elements Ni, Mn, Ti, Sr and especially Ag decrease from the top to the bottom of the mine. Co and Ba seem to have a slight tendency to increase with depth but in these cases the variation is very indefinite. It is interesting to compare these results with those obtained for the "Main" and "Siscoe" veins. In the "K" zone the points are rather regularly distributed and show very little scattering, but in the other two, the results are absolutely erratic and could not be plotted in a graph. This is probably due to the fact that the samples from these veins were collected wherever a grain of pyrite could be found regardless of location in the veins. In the "K" zone all of the samples came from different points in the zone, mostly along quartz lenses, but the rock is so highly sheared, crushed and broken that the solutions traveled uniformly through the zone, but in the veins, different parts of the orebody may represent pyrite of different ages.

A striking difference between the "K" zone and the veins at Siscoe is that all of the "K" zone samples contained abundant chromium (some contain so much of it that it cannot be determined quantitatively on the microphotomicrometer) while the same element is entirely lacking in the "Main" and "Siscoe" veins, which are a few hundred feet away. Another difference between the "Main" and "Siscoe" veins is illustrated by Ti, which is low in the former and very high in the latter. Yet, up to the present, all of these veins have been considered as strictly contemporaneous. It is believed that these differences in the content of minor elements strongly suggest a difference in age.

Comparison of Gold-quartz Veins and Massive Sulphide Deposits.

Silver shows a wide range of variation in both cases but the maximum content for this element, located in the intermediate

levels at the Hollinger Mine, is seen at the bottom of each orebody of massive sulphide at Noranda. Zinc shows a similar gradual variation in both types of deposits, but lead, which varies greatly in gold quartz veins, is very constant at Noranda. Nickel has a similar trend of variation in both cases, but cobalt does not show at the Hollinger Mine the decrease with depth observed in the "Lower H" orebody at Noranda. Chromium, present in small quantity at Hollinger, is very abundant in the "K" zone of Siscoe and absent in the gold-quartz veins of the same mine as well as in all of the samples from Noranda. A great scattering of the points is observed in all the pyrite from quartz veins, but all of the massive sulphide type, as well as the "K" zone of Siscoe, show a rather systematic variation.

The various differences pointed out above may possibly be due to the fact that the massive sulphide orebodies considered here, and also the Siscoe "K" zone, are much more homogeneous than the gold-quartz veins. In the latter type of deposits, samples came from all parts of the veins and even from different veins in the mine. It is suggested by Newhouse [13] that different portions of the same vein may very well represent different stages of deposition. This would very likely give a different content of minor elements in the accompanying pyrite. Such a theory seems to be demonstrated by the differences found in the minor elements of the pyrite from the different orebodies at the Siscoe mines.

QUEBEC, CANADA,
Dec. 12, 1940.

[13] Newhouse, W. H.: Personal communication, 1939.

GEOLOGY OF THE OMEGA MINE, LARDER LAKE, ONTARIO.*

C. P. JENNEY.

ABSTRACT.

The Larder Lake district lies along a narrow band of Timiskaming sediments which extends from Kenogami, Ontario, to beyond the Bell River in Quebec. On the Omega property, lavas and tuffs of the underlying Keewatin outcrop in the middle of this band in a sharply folded anticline overturned to the north. This anticline is broken by a thrust fault that follows the strike of the fold and along which the volcanics and sediments of the south limb have been up-thrown.

Later dikes and larger masses of granite, syenite, porphyry and lamprophyre intrude the older rocks. The Omega ore is, in part, an intrusive pegmatite of granitic composition that came in along the thrust fault on the hanging wall or south side, and, in part, an irregular replacement of the country rock (generally a green dacite) both adjacent to the intrusive and in a flow or flows on the northern limb of the structure. End stage igneous activity involved the introduction of large volumes of carbonates that completely or partially altered zones of the country rock to calcium, magnesium and iron carbonates.

INTRODUCTION.

THE property of the Omega Gold Mines, Limited, lies in the center of the southern part of McVittie Township in the Larder Lake district of Ontario (Fig. 1). The mine is located about one mile north of Larder Lake village on the Kirkland Lake-Rouyn highway.

Mining Development.—The original discovery on the surface outcrop of the Omega No. 1 ore zone was made in 1914. Intensive development was started in 1921 when Canadian Associated Goldfields and the Crown Reserve Mining Company sank two vertical three-compartment shafts 360 feet apart. The Goldfields shaft

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was eventually put down 1,000 feet, with six levels. The Crown Reserve shaft went to 1,175 feet, with nine levels. This shaft has recently been deepened to 1,550 feet and three lower levels are being opened at 125 foot intervals.

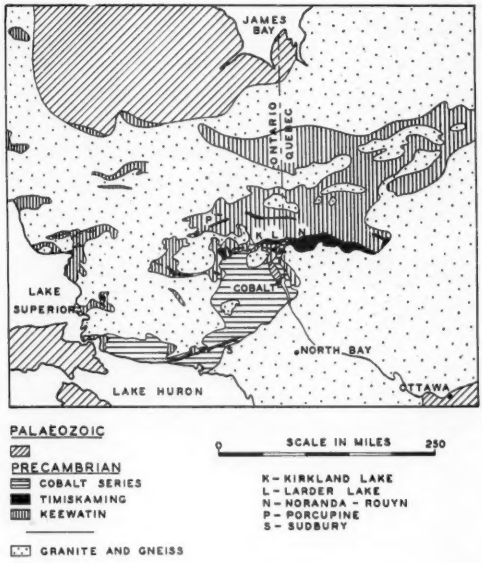


FIG. 1. Map of Northeastern Ontario and Western Quebec showing location of the principal mining districts.

Early development outlined ore shoots, mainly on the No. 1 zone along the thrust fault, although some values were found in veins 2 and 3 on the Crown Reserve. A mill (reported at 200 tons) was constructed by Associated Goldfields during 1926, and between April 1927 and March 1928 treated 22,585 tons for a recovery of $52,295.00. In 1929 both companies were shut down and subsequently amalgamated.

In 1935 the present company was formed and operated at 300 tons a day. From February 1, 1936 to March 31, 1940 (the end of the last fiscal year) 668,882 tons of ore were treated for a recovery of $3,171,842.34. The present mill is operating at 500 tons a day.

Earlier Geologic Work.—The first geologic reconnaissance of the district was made by W. G. Miller [1] who visited Larder Lake, then known as Lake Present. In 1903 W. A. Parks [2] described the geology along the chief waterways of the district. In June 1907 R. W. Brock [3] spent two weeks in and around Larder Lake and made the first detailed examination of the area. His assistant, Mr. N. L. Bowen [4] spent the remainder of the field season in the area and published a brief report and a more detailed map. In 1909 M. E. Wilson [5] examined the area from Larder Lake eastward into Quebec while his topographical party mapped the district. Between 1912 and 1919 A. G. Burrows, P. E. Hopkins, and C. W. Knight [6] did geologic work in the Swastika-Kirkland Lake area and in the vicinity of the Argonaut Mine. H. C. Cooke [7] in 1920 made a detailed map and examination of parts of McVittie and McGarry Townships, and in 1922 and 1923 P. E.

[1] Miller, W. G.: Lake Temiscaming to the height of land. Ont. Bur. Mines, XI: 214–230, 1902.

[2] Parks, W. A.: The geology of a district from Lake Timiskaming northward. Canada Geol. Surv., Sum. Rept., 1904, pp. 198–225.

[3] Brock, R. W.: The Larder Lake district. Ont. Bur. Mines, XVI, pt. 1: 202–220, 1907.

[4] Bowen, N. L.: Ont. Bur. Mines, XVII, 10–11, 1908.

[5] Wilson, M. E.: Larder Lake and eastward. Canada Geol. Surv., Sum. Rept., 1909, pp. 173–179; Geology and economic resources of the Larder Lake district, Ont. Canada Geol. Surv., Mem. 17: 1–57, 1912.

[6] Burrows, A. G., and Hopkins, P. E.: Kirkland Lake and Swastika gold areas. Ont. Bur. Mines, XXIII, pt. 2: 1–39, 1914; Burrows, A. G.: Gold in Gauthier Township. Ont. Bur. Mines, XXVI: 252–257, 1917; Hopkins, P. E.: Larder Lake gold area. Ont. Bur. Mines, XXVIII, pt. 2: 71–77, 1919; Knight, C. W.: Argonaut gold mine. Ont. Bur. Mines, XXIX, pt. 4: 65–76, 1920.

[7] Cooke, H. C.: Larder Lake district, Ontario. Canada Geol. Surv., Mem. 131: 17–61, 1922.

Hopkins [8] enlarged this map to include all of McVittie, McGarry, Hearst, and McFadden Townships.

ROCK FORMATIONS.

General Geology.—The Larder Lake District lies along a narrow band of Timiskaming sediments that extends from Kenogami station on the T. & N. O. Ry. east to beyond the Bell River in Quebec (Fig. 1). At Larder Lake lavas and tuffs of the under-

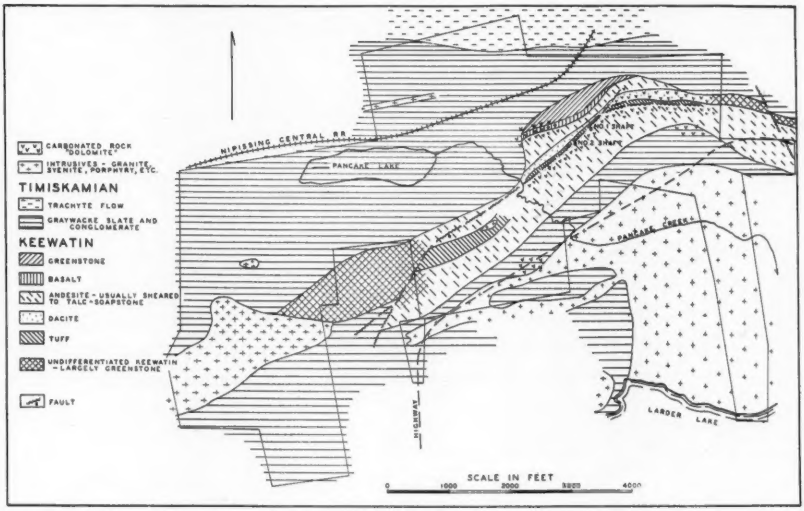


FIG. 2. Geologic map of the property of Omega Gold Mines, Limited, and vicinity.

lying Keewatin are associated with these sediments and outcrop along the same strike (Fig. 2). Later dikes and larger masses of granite, syenite, porphyry and lamprophyre intrude the older

[8] Hopkins, P. E.: Lebel and Gauthier townships. Ont. Bur. Mines, XXXII, pt. 4: 53–88, 1923; Hopkins, P. E.: Larder Lake area. Ont. Bur. Mines, XXXIII, pt. 3: 1–26, 1924.

rocks. Most of McFadden Township and a large part of McGarry Township are covered by sediments of the Cobalt series.

The following is a classification of the rocks of the district:

QUATERNARY
Pleistocene and Recent: Glacial drift and sand.
PRE-CAMBRIAN
Keweenawan (?): Diabase, lamprophyre.
Intrusive Contact.
Animikie
(Cobalt Series): Conglomerate, graywacke.
Unconformity.
Algoman: Granite, syenite, diorite,
granite poryhyry, quartz porphyry.
Intrusive Contact.
Timiskamian: Trachyte.
Graywacke, slate, some conglomerate.
Conglomerate, arkose, interbedded
graywacke.
Unconformity.
Keewatin: Greenstone, Basalt, Andesite, Dacite, Tuff } Omega Series.

Keewatin.

Since the earlier work in the district was of a more general nature, these rocks were grouped in two large, loose classifications as follows:[9]

Keewatin: Iron formation and tuff.
Altered basalt, diorite, diabase, gabbro and derivative carbonate, chlorite and other schists.

Detailed work by the writer has shown that on the Omega property and in the immediate vicinity the rocks mapped as iron formation and tuff are probably Timiskaming graywackes and slates with some iron formation. The Keewatin at the Omega consists of the following five members.

Tuff.—The oldest member of the Keewatin exposed in the underground workings at the Omega is a black and gray, generally fine-banded tuff. It varies up to 150 feet or more in thickness,

[9] See Hopkins, Cooke, etc.

and forms the footwall of the main "graphite" fault in the mine (Figs. 3, 4). In places, it contains lenses of the overlying dacite flow and toward the eastern part of the property the two are commonly interbedded.

The microscope shows the rock to have a fine-grained quartz-feldspar groundmass with occasional larger fragments of quartz, orthoclase and plagioclase. Much of the groundmass is recrystallized and some of the quartz and albite may have been introduced. The feldspars are commonly altered to sericite and actinolite but the rock as a whole is less altered than the overlying greenstones. Some fine leucoxene is present in places and quartz, carbonate and pyrite have been introduced in varying amounts. The dark and light banding is distinct and is apparently due to carbonaceous material in the different layers.

Dacite.—Overlying the tuff horizon is a coarse, massive green to gray or brown lava of intermediate composition, which carries numerous small quartz phenocrysts. It varies in thickness from 80 to 130 feet. The lower part of this formation (that adjacent to the tuff) is generally dark green and carries much prominent leucoxene in shreds. It is within this portion of the lava that a large part of the replacement ores known as Nos. 2 and 4 veins occur. Throughout this horizon, but especially in the vicinity of the ore, the dacite contains narrow bands (generally one-eighth inch to one inch) of dark chert-like siliceous material that has commonly been selectively replaced by massive pyrite and nodules of marcasite.

The upper part of the dacite is commonly altered by introduced carbonates to a gray or brown color. In places the top of the dacite flow is marked by a narrow section of fragmental and carbonaceous material, but more commonly there is a sharp contact with the overlying andesite.

In thin section the dacite is revealed as a porphyritic and siliceous rock. It is made up of numerous quartz phenocrysts up to 1 mm. in diameter in a quartz-feldspar groundmass. A good deal of titanite and some titaniferous magnetite are present as accessories and have been altered to leucoxene. The rock on

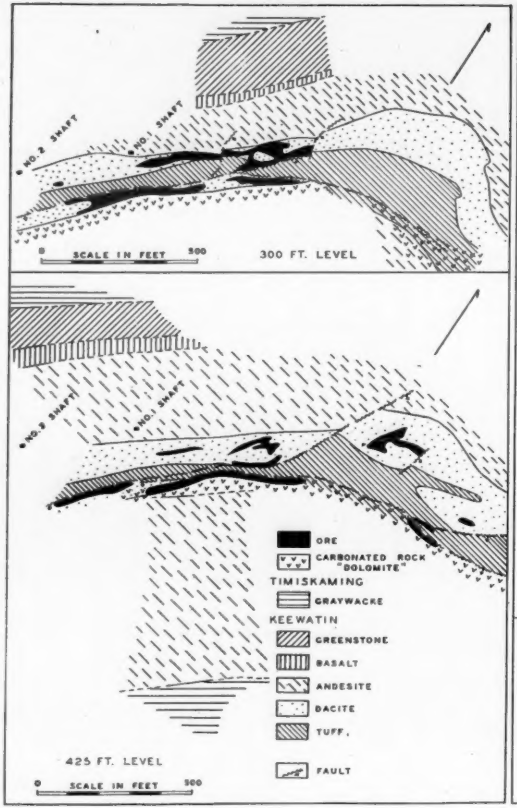
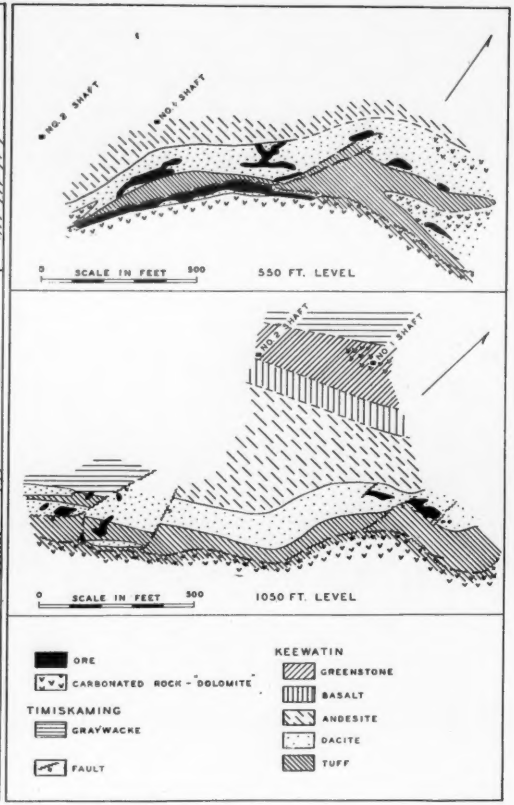

NO. 2 SHAFT
NO. 1 SHAFT
0 SCALE IN FEET 500
300 FT. LEVEL
425 FT. LEVEL
ORE
CARBONATED ROCK - DOLOMITE
TIMISKAMING
GRAYWACKE
KEEWATIN
GREENSTONE
BASALT
ANDESITE
DACITE
TUFF
FAULT

FIG. 3.


NO. 2 SHAFT
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1050 FT. LEVEL
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CARBONATED ROCK - DOLOMITE
TIMISKAMING
GRAYWACKE
FAULT
KEEWATIN
GREENSTONE
BASALT
ANDESITE
DACITE
TUFF

FIG. 4.

the whole is fairly fresh with a few of the feldspars altered to sericite. The green color is due to the presence of chlorite. Antigorite is also present. Quartz, calcite and pyrite have been introduced and graphic intergrowths of quartz and feldspar are common in the introduced material.

Some shear structure is shown by sericite wrapping around lenticular areas of groundmass and rounded or broken quartz phenocrysts. These phenocrysts are cut by veinlets of the introduced material and chlorite, and are embayed by areas of groundmass and its alteration products. Some sections show a liberal dusting of very fine dark carbonaceous (?) material throughout the groundmass.

Petrographically this rock is probably best described as a porphyritic rhyolite but due to the similarity to the dacite flows in the Porcupine District and the indeterminate character of the feldspar of the groundmass, the name dacite, already in use at the mine, has been retained.

Andesite.—Overlying the dacite is a highly sheared and altered rock generally referred to as a talc-soapstone. It varies in color from a dark brown or black to a light gray or green. Its thickness is approximately 225 feet, but it ranges from 170 to 350 feet. The shearing is less striking on the surface, where it is exposed on the hill from the mill to the crusher house. In the No. 1 shaft crosscuts it is best described as a schist with only a few black elliptical areas of massive material. The overlying fine-grained basalt may be a chilled top portion of the andesite, since similar basalt-like areas occur within it near its top.

In some of the No. 2 shaft crosscuts the andesite is more massive and in places where quartz phenocrysts are not prominent in the dacite, the two form an indivisible massive greenstone.

Under the microscope the extreme alteration of this rock is apparent. What was a fine to medium grained mass of short

FIG. 4.

FIG. 3.

FIG. 3 (Left). Geologic plan of 300- and 425-foot levels, Omega Mine. (Mine workings omitted for clarity.)

FIG. 4 (Right). Geologic plan of 550- and 1050-foot levels, Omega Mine. (Mine workings omitted for clarity.)

feldspar laths (mostly oligoclase-andesine) with some hornblende and a little biotite is altered to a matted mass of actinolite, sericite, chlorite, carbonate and leucoxene. Some titanite, magnetite and rutile were originally present as accessories. No phenocrysts of quartz or any other mineral are present although quartz and calcite have been introduced later. Veinlets of crysotile and some introduced pyrite were also noted.

Basalt.—On the surface outcrop north of the crusher house and on the 800-foot and lower levels north of the main fault, a dense, fine-grained, green rock, about 60 to 80 feet wide, overlies the andesite. In places the two are intercalated and it is highly probable that this horizon represents a chilled top of the andesite flow. Due to its fine grain it was designated basalt by the original operators from McIntyre Porcupine and, to avoid confusion, this name has been retained.

In the south crosscuts on the 425 and 800 levels this basalt is not recognizable. However, its stratigraphic position is occupied by some 75 feet of conglomerate overlain by 50 feet of black tuff and fine-grained, gray to black lava.

Petrographically the basalt consists of a fine-grained, quartz-feldspar-chlorite groundmass through which some crystals of quartz are distributed. Most of these have been introduced but a few may be original. A good deal of the feldspar has been altered to sericite and the titaniferous magnetite, which is in places liberally scattered through the rock, is surrounded by halos of, and penetrated along fractures by, leucoxene. Both quartz and calcite have been introduced. No indication of the original ferromagnesian mineral is left and no olivine is present. The rock is probably an andesite.

Greenstone.—North of the basalt, on the outcrop north-west of the crusher house and on the 925-foot and lower levels, is a coarse, green, chloritic lava. It is similar in composition to the older Keewatin lavas described above but carries no quartz phenocrysts. It is a typical greenstone and is so designated in order to differentiate it from the other flows. On the lower levels it varies in thickness from 115 to 190 feet but on the surface attains a

maximum of 380 feet. On the surface some poorly-developed pillow structure can be seen and, on the 1175-foot level, near the top of the formation some interbedded tuffs occur adjacent to the overlying graywacke. In the south crosscuts and in drilling to the south this greenstone has been found to include massive sections similar to the typical material on the north limb of the fold but to consist largely of spherulitic pillow lavas. The pillows are commonly poorly developed, as they are on the surface, but the spherulitic structure is generally well developed and typical of this flow on the southern limb.

Timiskamian.

Sediments.—Unconformably overlying the Keewatin and infolded with it in the main structures of the area are thick sections of Timiskamian sediments. These cover at least 50 per cent of the Omega ground, bounding the band of Keewatin greenstones on the north and south.

Where examined, these sediments were found to be largely graywackes with interbedded slates, although a good deal of conglomerate and some arkose are included near the base of the series.

Cooke[10] states that the conglomerate varies from zero to a thickness of 600 feet. It makes up a large part of the hill south of the Omega No. 2 shaft, where the matrix is a sheared, sandy graywacke with some slate in one or two places. The pebbles, which are numerous, are generally well rounded and elongated by shearing, and consist of porphyry, granite, syenite, quartz, greenstone, iron formation, red jasper and chert.

The conglomerate is also exposed in the southern end of the long crosscut on the 425-foot level. Here the pebbles are much less numerous than on the hill to the south and the whole formation is much more highly sheared. This is also true of the formation where it is cut by a drill hole from the edge of the intrusive to the end of the 425-foot level crosscut. Some of the pebbles from this horizon, when examined microscopically, proved to be highly

[10] *Op. cit.*, p. 23.

altered syenite porphyry with well developed orthoclase phenocrysts.

North of the dolomitized greenstone and near the base of the Timiskaming sediments a thick section of arkose was encountered in a drill hole on the property of the Fernland Gold Mines Limited, which adjoins the Omega to the east. This core was examined by the writer and is fresh, coarse material with well preserved orthoclase and plagioclase crystals embedded in a finer grained groundmass. Its thickness in this hole is unknown.

A drill hole on the northeastern part of the Omega property showed a thickness of 75 feet of similar material about 400 feet above the base of the Timiskaming. This drill hole bottomed in the arkose so its true thickness is not known.

The graywacke, which makes up the bulk of the Timiskaming sediments, is a light to dark gray massive rock in places rendered schistose by heavy shearing. Under the microscope it is seen to be sandy grit with coarser and finer bands made up largely of quartz. Some orthoclase and plagioclase are also present and the ferromagnesian minerals (probably hornblende) are altered to chlorite. The feldspars are altered to sericite.

Much titaniferous magnetite, altered to leucoxene, occurs in zones. The quartz grains are very angular for the most part, although some show a little rounding. Sparse beds of very coarse material throughout the formation might be described as conglomerate, but even this coarser material is distinctly angular.

With diminution of grain size (and perhaps the addition of some carbonaceous material) the graywackes grade into slates. These form partings in the coarser and generally lighter colored beds and clearly indicate the attitude of the series. In the outcrop just north of the railroad, west of Larder Lake station, sharp local folding is well shown by this contrast between the graywackes and interbedded slates. South of Pancake Lake, a good deal of iron formation consisting of magnetite and red jasper occurs within the graywacke-slate series. These rocks were formerly assigned to the Keewatin by Cooke and Hopkins but their similarity to the graywackes of the surface and of the

underground workings south of, and beneath them, indicate that they are Timiskaming.

Trachyte.—Extending slightly south of east across the northern part of the area shown in Fig. 2 is a coarse grained porphyritic lava of a gray-brown or reddish-brown color. It closely resembles the intrusives of the district in appearance and composition but is a Timiskaming flow rock. It has been described by Cooke [11] who has examined it in many different localities in the Larder Lake district.

The writer has studied this flow only on the Omega property and the adjacent ground to the north, which is its basal portion. At one point in this area the lava is highly amygdaloidal and also coarsely porphyritic, this section being close to the bottom of the flow.

The microscope discloses lath-shaped phenocrysts of feldspar and, in some sections, phenocrysts of hornblende in a fine-grained, feldspar groundmass. The feldspars show varying degrees of alteration to sericite and carbonates and most of them are kaolinized. The hornblende, where present, is invariably altered through biotite to chlorite.

Accessory minerals are titanite, which has altered to leucoxene, and magnetite, titaniferous magnetite and epidote.

The amygdaloidal specimen mentioned above is a fresh rock with phenocrysts of albite, orthoclase and anorthoclase, up to 2 mm. in length, in a fine-grained groundmass. Numerous vesicles up to 2 mm. in diameter filled with later quartz and some sericite are scattered throughout the section. A little introduced quartz is also present. The ferromagnesian minerals are present as small crystals in the groundmass.

Cooke has called this lava a soda-trachyte, indicating that it is the effusive equivalent of a hornblende syenite rich in soda. The only variation from Cooke's description found by the writer was the lack of hornblende in some specimens. No flow structure was seen since the specimens examined are all massive porphyries.

[11] *Op. cit.*, pp. 24–26.

Algoman.

Intrusives of post-Timiskaming age are numerous in and around Larder Lake village and the Omega property. These have been described in detail by Cooke [12] but certain modifications in the rock classification appear justified. In the area covered by the accompanying surface map (Fig. 2) the intrusives identified are: hornblende lamprophyre, granite, granite porphyry, syenite, and quartz porphyry.

Hornblende Lamprophyre.—A few dikes of this type have been found by Cooke and described as follows: [13]

> It is composed of about 35 per cent of reddish-white feldspar, with perhaps 5 per cent of biotite, the remainder roughly equidimensional crystals of hornblende 2 to 4 mm. in diameter, now largely altered to chlorite.

Cooke found these dikes parallel to the Timiskaming bedding in most places, and that they were faulted during the post-Timiskaming folding. They are also cut by the later granite. Some old intrusives, which may be similar to these dikes, were found interbedded with the Timiskaming conglomerate in the south end of the 425-foot level crosscut. These were not examined microscopically but are tentatively correlated with the above.

Granite.—Most of the intrusives shown in Fig. 2 are true granites, and other varieties are so closely related that they have been mapped as a unit. The typical granite is a brownish or gray rock weathering light gray, with feldspar and quartz phenocrysts apparent in some of its porphyritic phases. It consists of quartz, orthoclase and plagioclase (varying from albite to andesine) with hornblende commonly present in sufficient quantities to be an essential mineral. In all of the sections examined more orthoclase than plagioclase was present and in all but one, quartz was present in sufficient quantity to be essential. Consequently, the name granite and granite porphyry seems more applicable than Cooke's diorite and diorite porphyry designation. Accessory minerals are

[12] *Op. cit.*, pp. 43–47.
[13] *Op. cit.*, p. 43.

magnetite, titanite, apatite and hornblende. Many of the rocks are fairly fresh but in some the feldspars have been highly sericitized and kaolinized. The hornblende is commonly altered to biotite and chlorite, and quartz, calcite and pyrite have been introduced.

The following are a few variations from the typical granite:

A specimen from the outcrop on the highway 1800 feet west of Pancake Creek shows a higher percentage of ferromagnesian minerals than customary, and much less quartz. However, orthoclase is more common than plagioclase and some quartz is present. It might be classified as either a granite or quartz syenite.

A section from the large hill on the southern part of the west boundary discloses a coarse granite with orthoclase crystals up to 6 mm. and hornblende up to 1.5 mm. in length. The hornblende in this rock is more highly altered to chlorite than usual but the other minerals are quite fresh with only slight kaolinization of the feldspar.

Another specimen from the shore of Larder Lake 100 feet east of the Omega pipe line is a quartz porphyry. Numerous quartz phenocrysts up to .5 mm. in diameter and a few feldspar phenocrysts are present in an altered finely granitoid groundmass.

A dike of granite porphyry 70–80 feet wide crosses the northern part of the Omega property in an east-west direction. Considerable trenching was done on the eastern end of this dike and an old drill hole was put down across it. No records are available of the results of this work but quartz veins carrying pyrite, arsenopyrite and gold are said to occur within the intrusive.

A specimen from the west end of this dike as shown in Fig. 2 is a highly-altered granite porphyry. Relict structures of old feldspar and hornblende phenocrysts, now altered to carbonates, sericite, magnetite and chlorite, are present in a highly carbonated and sericitized groundmass.

Animikie (Cobalt Series).

Conglomerate.—One small outcrop of the basal conglomerate of the Cobalt Series occurs on the south side of the Rouyn-Kirk-

land Lake highway at the point where the southern contact of the Timiskaming sediments crosses the road. This outcrop is too small to show accurately on the surface map (Fig. 2) so was omitted from the map and legend. Other outcrops shown by Cooke and Hopkins on the hill south of Pancake Creek are Timiskaming conglomerates. A detailed description of the lithology of the Cobalt Series was published by Wilson.[14]

Keweenawan (?).

Diabase.—Hopkins [15] has reported quartz diabase dikes in McVittie, McFadden and Hearst Townships that cut the Keewatin, Timiskamian and Algoman but were not seen actually to cut the Cobalt Series. No diabase has been found in the Omega vicinity.

Lamprophyre.—Numerous dikes of biotite lamprophyre of the minette type have been found in the Omega underground workings although none have been seen on the surface. They vary in thickness from a few inches to a foot or two and do not extend far either horizontally or vertically. The lamprophyre cuts all the other rocks of the area shown in Fig. 2. Its relation with the Cobalt Series is unknown. It is generally dark brown or gray-brown but in places, where it cuts the graphitic fault zone, it is light gray or white. These dikes are too small for accurate representation on the accompanying level plans (Figs. 3, 4).

The lamprophyres are typically porphyritic rocks with numerous phenocrysts of orthoclase and biotite varying up to 2 and 3 mm. in length in a fine-grained, altered groundmass. Accessories are titanite and magnetite and much fine biotite is present in the groundmass. The rocks are all highly altered, the biotite is changed to chlorite with some limonite and rutile, and the orthoclase is completely altered to carbonates, quartz and some fresh feldspar. Much of the fine biotite wraps around the old orthoclase phenocrysts in typical ophitic structure.

[14] Wilson, M. E.: Larder Lake district, Ont. Canada Geol. Surv., Mem. 17-E: 35-37, 1912.

[15] Hopkins, *op. cit.*, p. 10.

Pleistocene and Recent.

Glacial Drift and Sand.—The pre-Cambrian rocks of the area are largely covered by glacial sands and gravel, by Pancake Lake, and slimes from the mine. On the Omega property there are only 143 acres of outcrop, which represents 18 per cent of the surface area. In the vicinity of the mine a large part of the geology shown in Fig. 2 is projected from underground workings and drill holes. Elsewhere, in sections of few outcrops, much of the surface geology must be inferred.

STRUCTURE.

Folding.—The major structural feature of the area mapped is a closely folded, eroded, overturned anticline, extending roughly northeast and southwest, which exposes the Keewatin lavas and tuffs between bands of Timiskamian sediments. The axis of this fold lies within the band of tuff that marks the base of the exposed Keewatin and trends approximately N. 55° E. near the western boundary of the property. A short distance east of No. 1 shaft it swings due east.

The flows in this major structure show a fairly uniform dip of 70° to the south on both sides of the axis, although many local variations occur. Crosscuts in the graywacke to the north fail to show any noticeable angular unconformity between the two series at these points, the dip of the original bedding being approximately 70° south. The sediments underlie the Keewatin on the north limb of the fold at the 1050 and lower levels (Fig. 5). In drilling, and in places in these crosscuts, a definite sedimentary gradation is found, which indicates that the Timiskamian faces north and is overturned. Some suggestion of arching is occasionally encountered in stoping in the dacite of No. 1 Zone. This structure is rare and generally poorly developed, due to the massive character of the dacite and the fact that this part of the flow was well down on the south side of the fold.

Two large outcrops of massive greenstone comprise the western 2,000 feet of the Keewatin lavas. Still further west, this band

of Keewatin is shown as passing beneath the Timiskaming sediments and displaced by later intrusives.

At No. 1 shaft the exposed Keewatin is a little over 1,200 feet wide but narrows to the east and west. The younger members of the series encountered in the No. 1 shaft crosscuts do not continue to the west, where their place is taken by Timiskaming sediments. This may be due to the presence of a transverse

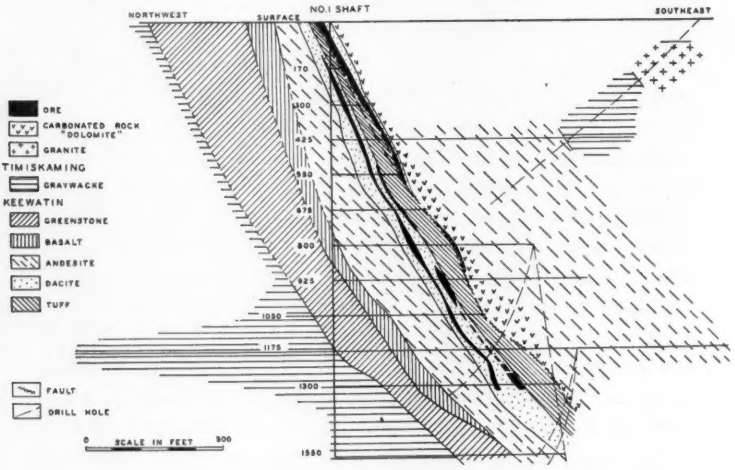

FIG. 5. Geologic section N. 45° W. through No. 1 shaft, Omega Mine. Note: geology on southern half of 1300-foot level offset 200 feet east; ore below 1300-foot level not shown.

cross-fold or to differential erosion on the old Keewatin surface before deposition of the Timiskaming. The latter seems the more logical explanation since no evidence of cross-folding is shown by the exposed Timiskaming sediments. East of the main Omega workings the Keewatin band also narrows to about 500 feet and passes onto the Fernland property trending slightly south of east.

Faulting.—The most striking structural feature seen underground is the "graphite" fault, so-called because of its charac-

teristic wide zone of graphitic gouge (Fig. 5). It trends about N. 45–55° E. and has been traced underground and in surface drilling for one mile. The crush zone varies in width from a few inches to five feet or more and in places splits into two or three branches, each a pronounced fault zone. It dips south at an average angle of 55° to 60° and, therefore, cuts the Keewatin volcanics at a slight angle. It is a thrust fault with the southern side upthrown.

Within the mine workings the Keewatin tuffs everywhere underly the fault plane. From the surface to the 675-foot level a wedge of dacite adjoins the ore to the south of the fault. This wedge is cut out at the 675-foot level and its continuation must lie beneath the fault at some lower horizon. Since it was not encountered on the 1550-foot level, the vertical throw on the fault must be at least 900 feet and is probably a great deal more.

In general strike the graphite fault is fairly straight along the N. 45°–55° E. trend for a distance of some 3,000 feet. On the east end it breaks into three or more branches and swings more to the east. Information from two diamond drill holes indicates that this also may be the case on the west end, although the surface geology suggests a swing to the south at the west end as shown in Fig. 2. Detailed mapping shows that the course of the fault, both along the strike and dip, is remarkably irregular and sinuous. On some of the levels it makes sharp right-angled bends with subsidiary cross-faults commonly radiating from these points. Such a cross-fault on the 1000-foot level displaces the dacite-tuff contact in the eastern block some 50 feet to the north (Fig. 4 shows this feature on the 1050-foot level). Another branch fault on the 1175-foot level displaces the dacite on the east side of the break over 50 feet to the north, and something less than 100 feet to the east. This would indicate that the thrust had some horizontal component to the east.

The pattern of these small branch faults and related jointing is considered very important in the localization of the replacement ores within the dacite flow. On the 300-foot level the extensive development of No. 4 vein may be due to the numerous

cross-fractures in this area (Fig. 3). On the 425-foot level the south body of the western section of No. 4 vein lies along a branch fault and numerous small breaks run through the eastern section of the same vein (Fig. 3). On the same level two small ore bodies have been found along branches of the main fault to the east in No. 1 zone. On both the 800- and 925-foot levels the relation between branch faults and the No. 4 replacement body is very striking. A suggestion of the same relationship is found in the western ore bodies and related faults on the 1050-foot level (Fig. 4).

Movement along the main "graphite" fault continued after the introduction of the ore-bearing pegmatitic material as evidenced by the presence in the fault gouge of vein fragments, in places coated with graphite. In places, large pieces of red ore are dragged and broken by late movement along the fault. Numerous nodules of marcasite coated with, and embedded in, graphite are also characteristic of the fault zone. However, the main faulting movement was largely pre-ore.

ORE DEPOSITS.

Mode of Occurrence.—The Omega ore consists of two closely related types: the pink or gray orè most commonly found along the No. 1 zone and made up entirely of introduced material, and the dacitic or country rock ore, which is essentially an alteration and replacement of pre-existing rock with only minor amounts of introduced material. The ore of zones 2 and 4 is largely of this second type.

The No. 1 vein lies on the hanging-wall side of the "graphite" fault and is generally widest where the fault bends slightly to the north. A good deal of replacement ore is included with the introduced material in the dacite above the 675-foot level, and mining is carried to assay walls on the south side of the vein. Where no dacite is present along the south side of the fault, the ore is largely introduced vein material and its contact with the "dolomite" to the south is sharp. The presence of the vein in close proximity

to the fault along its strike and dip would indicate that it guided the mineralizing solutions (Figs. 3, 4, 5).

Veins 2, 4, 6 and 7 are largely replacement bodies and usually are found within the dacite flow that overlies the tuff north of the fault. Small branches from the main fault seem to have guided the incoming solutions and served to localize the ore bodies as outlined above under faulting. Rarely, tuff is replaced by these ores as is the case near the west end of the 1,050-foot level (Fig. 4). All gradations exist between complete replacement and unaltered country rock so that mining must be carried to assay walls, and stope plans are very irregular.

Irregularities are also quite marked in the vertical extent of the replacement ores giving the bodies a lens-like form. Some of these lenses show a steep eastward rake probably due to the folding of the dacite flow. Ore frequently is found in the dacite adjacent to the overhanging tuff contact, which may have had a ponding effect in places.

Mineralogy and Structure.—The introduced material of No. 1 vein is of two distinct types, a red and a gray variety. The red or pink ore is essentially pegmatitic granitic material made up of quartz and albite with some orthoclase. Titanite and magnetite are present as accessories. Consequently, the rock is similar in composition to the intrusives of the adjacent area. All sections of the pegmatite show crushing and shearing and small veinlets of quartz and carbonate ramify in all directions. Pyrite and arsenopyrite and, in places, some chalcopyrite were introduced. Visible gold (with a gold-silver ratio of 7:1) has been found in a few places but is rare. Gold may also be seen under the microscope in cracks in the pyrite and arsenopyrite. The reddish color of the ore is due to limonite derived from the magnetite. Both the red and gray ores characteristically show graphic intergrowths of quartz and feldspar.

The gray ore is similar to the red in composition except for the lack of magnetite. Some titaniferous magnetite is present and is altered to leucoxene. Grain texture is finer and more uniform in the gray ore, being typically granitoid rather than peg-

matitic. The gray ore is commonly much more altered to sericite and carbonates than the red, which is quite fresh. It generally carries veinlets of chlorite and actinolite. Both ore types show intrusive relations with the country rock and were described as granite dikes by the early operators.

The replacement ores show the same end-stage alteration effects as those found in the gray ore and all variations exist between fairly fresh country rock and areas carrying a large percentage of introduced material. The ore minerals are also the same as those found in the introduced veins.

Paragenesis and Origin.—The similarity between the Omega ore and many of the deposits recently discussed by Gallagher [16] is very striking. The general sequence of paragenesis at Omega is: quartz and silicates, iron sulphides, gold, quartz and carbonates. The gangue minerals quartz, albite and carbonates are abundant. Undoubtedly the gray ore was the earlier for it shows a good deal of hydrothermal alteration and granitoid texture compared to the fresh pegmatitic appearance of the red ore.

Evidence for the origin of the ore-bearing solutions is very suggestive in this case. A large body of albite-rich granite lies close to the deposit on the south and west and small apophyses of the same type outcrop at other places on the property. The ores seem to have been guided to their present position by a very strong south-dipping fault. This break probably formed part of a channel way that tapped the magma reservoir from which the granites were derived.

CARBONATE ROCK OR "DOLOMITE."

Bands of carbonate rocks consisting of calcium, magnesium and iron carbonates are numerous in the Larder Lake district. These have been described by Brock,[17] Wilson,[18] Cooke,[19] and Hopkins,[20] Cooke's work on them being particularly thorough.

[16] Gallagher, David: Albite and gold. ECON. GEOL., 35: 698–736, 1940.
[17] *Op. cit.*, pp. 207, 215.
[18] Canada Geol. Surv., Sum. Rept., 1909, p. 175.
[19] *Op. cit.*, pp. 48–55.
[20] Ont. Bur. Mines, 33, pt. 3: 8 and 9, 1924.

They are secondary in origin and due to the replacement of the country rock by magmatic solutions high in carbonates. Where alteration has been complete, the rock is a light cream or bright green color, in the latter case due to the presence of numerous flakes of chrome mica, determined by Wilson [21] as fuchsite or mariposite. In the Larder Lake district these carbonated areas have become known as gray and green dolomite.

Where dolomitization is pronounced, numerous narrow quartz stringers, which vary from about two inches to microscopic size, are present. These ramify in all directions and commonly form an intricate lace work throughout the carbonated area. They are mostly filled with quartz and calcite with some albite in places. Most quartz veins of the district show carbonated areas on both sides indicating that the solutions emanated from the vein. Much of the carbonated rock is also highly schisted and is best described as dolomite schist. Quartz veins and stringers are commonly present in the schist.

The main area of dolomitization at the Omega lies south of the dacite flow of No. 1 ore zone where it is present along the graphite fault, and forms the hanging wall of the graphite fault where no ore or dacite is present. It is about thirty or more feet wide and has a sharp contact with the dacite or ore on the north and fades gradually into the schisted andesite formation to the south. It extends through the property for a distance of at least 3,000 feet. In the eastern part of the mine, where the main fault breaks into a number of branches, at least two other carbonate zones were found underground and in drilling. One of these extends eastward onto the Fernland property.

Other small dolomitized areas occur throughout the mine, the most noteworthy being the zone of No. 3 vein in the shaft and on the 300-foot level, where visible gold has been found. Surface areas of dolomite are shown in Fig. 2. Evidence of the secondary nature of the dolomite is shown in many of these occurrences where dolomitized areas cross the original bedding of the rocks.

[21] Canada Geol. Surv., Mem. 39: 65–70, 1914.

Cooke[22] has outlined the sequence of mineral alteration in a study of more than 100 thin sections from dolomite zones of the district. He finds that the first stage of alteration is introduction of ankerite, producing banded structure along shear zones. The ferromagnesian minerals were then attacked and replaced by carbonate, the feldspars went next, and the quartz was the last to be altered. All stages of replacement have been traced under the microscope and where complete the rock was a massive ankerite body.

Cooke accounts for the greater number of veins near the center of a dolomite band by postulating a program of progressive fissuring, whereby increase of volume due to addition of ankerite caused renewed fracturing that would be more active where carbonate replacement had been most complete. He also traced progressive changes in vein composition from the quartz-calcite veins of the completely altered dolomite zones to pure ankerite veins in the partially altered country rock. However, he then states that there can be no age difference between these veins as the composition of a single vein varies along the strike. The writer agrees that there is no essential age difference between the veins and considers the variation in intensity of dolomitization to be merely a function of the distance from the source of the altering solutions.

The carbonating solutions were operating after the intrusion of the granites of the area for they are, in places, altered to dolomite, and also after the deformation of the Timiskaming since dolomite bands cut across folds in the sediments. Fragments of dolomite have been reported from the basal conglomerate of the Cobalt series so the dolomite is evidently pre-Cobalt. Some carbonate alteration of the country rock took place over wide areas, apparently some distance from an igneous intrusive. This may indicate a wave of carbonating solutions that preceded the advancing intrusion. However, the main dolomitizing solutions evidently emanated from the same magma that produced the other intrusives of the district probably very soon after the introduction of the pegmatites represented by the Omega ores.

[22] *Op. cit.*, p. 52.

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McINTYRE PORCUPINE MINES, LIMITED,
SCHUMACHER, ONTARIO,
Jan. 2, 1941.

GRANITE AND ORE.

AUGUSTUS LOCKE.

ABSTRACT.

The accepted alliance of ore with intrusive igneous rock may be discussed in terms of granite, for granite is regarded as the predominant rock of this kind. However, much granite has been observed in recent years which seems to be, not "magmatic"—that is, not intrusive and igneous—but "metamorphic." This second kind of granite is thought to be at the end of a metamorphic series that started in great part with marine sediments; it is, essentially, recrystallized mud.

How is the theory of ore genesis affected by what we know of this metamorphic granite?

In the recent treatments of "The Nature of the Ore-Forming Fluid" by Graton, Ingerson, Morey, and Fenner,[1] as in many other papers on ore genesis, the magma reservoir is used as the fundamental. The idea of the derivation of the ore from this reservoir is taken from the close field association between ore and intrusive igneous rock; if the rock has ascended from a reservoir of melt, the ore is believed to have come from a similar source. But it is now realized that the predominant intrusive igneous rock, granite, may have another and quite contrasted origin. A view of this rock that was held at various times in the past has lately come back into favor, but with improved reason, for observers have been bringing in from every continent formidable evidence indicating granite that is not magmatic at all but is merely recrystallized schist and quartzite. Moreover, many gradations ending in such granite have been retraced from granite to schist, schist to shale, and shale to mud, and it is clear that additional examples of this series will be found. Much granite, then, is regarded as a metamorphic rock which, essentially, is recrystallized mud. Its fundamental is, not a magma reservoir, but the detritus accumulating on the sea bottom. Recognizing two divisions of

[1] Econ. Geol., vol. 35, March, September, and November, 1940.

concept regarding the origin of granite, geology is not at liberty to take the one and, for an indefinite time, leave the other. It has to take them both and follow them through. Graton and the others have fixed their attention on magmatic granite. In this paper the reader is invited to look toward metamorphic granite and to consider the effect which its history may have on the idea of ore.

It will be realized that the difference between magmatic and metamorphic granite is profound. The latter is indigenous to the structure in which it now lies, for, essentially, it grew there. Though it moved upward in that structure, its movement may be regarded as of the same order as that of an anticlinal core or of the overthrust part of an anticline. Instead of being a foreign material imported from some distant place, it is thought to have grown at nodes of turbulence where the rock has been especially dragged and broken. Its general occurrence fits in with this idea, for all the great metamorphic tracts of the world carry granite here and there, as though the schist were unstable and were poised on the brink of going over to that rock. In proportion as this interpretation is found to fit, the reason fades for the belief that the granite in question came from an abyssal source, or that it is any more likely to increase in bulk downward than is a body of schist or marble; its outside contacts and the structures both external and internal become the guides for its downward projection. The genesis of such granite can be studied in its structural setting, for that setting is its "manufactory."

The magmatic granite, on the other hand, has come up from a distant, deep, foreign place. Instead of growing from the other rocks of the structure, this granite has abruptly broken in among them. The separation of the granite-forming fluids, and also of the ore-forming fluids, took place far away in the magma reservoir, by differentiation there in a melt. Such granite is not subject to direct study, from the standpoint of genesis, for the reservoir lies deeply hidden.

Evidently, in choosing to tie an ore to the magma reservoir, as Graton and many others do, the geologist commits himself to a distinction between the two kinds of granite, and determines that

the particular granite body is magmatic and not metamorphic. How does he reach this conclusion?

He reaches this conclusion through evidence in carefully mapped bodies that the granite has moved upward in relation to its walls, for the contacts are often sharp and the linear elements such as hornblende, which betray the direction of elongation, have a steep pitch. When scrutinized, however, this conclusion is seen not to be a unique interpretation of this evidence; for, while the direction is indisputable, the supposed magnitude of the movement takes the form of an assumption unsupported by even the roughest quantitative measurements. This assumption, moreover, is contrary to the results of much recent mapping which, revealing systematic internal patterns, suggests that the movement has been moderate. In other words, when the most ample data are consulted, they often do not seem to imply an ascent by the granite of more than a few feet or a few hundred feet, leaving it still within what may be called its native habitat. Although such granite may be sharply bounded, it has been found near its borders to be crowded with large and small remnants of schist, quartzite, marble, and other wall rocks. Toward the interior, these stream out into curved lines made up not only of the remnants but also of the so-called "autoliths," schlieren, and even crystals of tabular habit such as feldspar and mica. These, as mapping progresses, are found to compose into systematic patterns, sometimes of steep drag folds, fitting into the structures of the surrounding rocks.

In spite of the usual sharpness of the contact and the cross-cutting nature of that contact, the remnants and the structure patterns effectively keep the granite attached to the wall structure. The contact, practically, resembles a fault, and the inclusions are the relics of drag between the solid ground on the wall side and the broken, perhaps comminuted ground on the granite side. It thus appears that the two, seemingly contradictory, bodies of evidence may really lead to the same result.

However, in the interior part of the granite, well inside the walls, the trail is often lost, and all that is known is that the material seems to have come upward. How far has such material,

when actual evidence of distance is missing, come upward? Some of it, in physical continuation with the granite considered metamorphic, is merely rock of the same kind in which recrystallization and effacement are complete. But some of it, as may be supposed, is of a wholly different origin, and has been pumped from unknown depth. Unfortunately, no means has yet been found to distinguish these two granites from each other. Moreover, the geologist will appreciate that he has no right, because in a given case the distance of upward travel is unknown, to assume that it is large; for no one has yet found a way, once he is off the trail, to separate the evidence of a travel of 500 feet from that of five miles, or even of 50 miles. In other words, the identification of a part of the granite as metamorphic seems specific and positive. The identification of a part of the remaining granite as magmatic is made on the basis of general ideas and the proportion of such granite to all granite is being reduced as mapping progresses in various parts of the world. The Sierra Nevada mapping of 1930–1940,[2] for example, has continually disclosed new areas of metamorphic granite without proving other origin for any granite whatever. Indeed the question may well be asked—what would constitute proof of magmatic origin?

Fixing attention then on the evidence relating to metamorphic origin, let us come back to the question proposed at the beginning of this paper. How does this evidence affect the idea of the nature of ore? For example, is ore connected in the field only with the granite of magmatic origin? Or, to put it in other words —to what extent is the granite with which ore is associated truly "intrusive and igneous"? Is there no suggestion in the field of ore associated with metamorphic granite? Is there no reasonable genetic alliance between ore and metamorphic rock?

This subject remains neglected in the American literature. As in the Graton paper and the discussions following it, magmatic origin has by custom been regarded as so well known that such an alternative as this need not be mentioned. Indeed it is only

[2] Locke, Augustus, Billingsley, Paul, and Mayo, E. B. (1940): Sierra Nevada Tectonic Pattern, Geol. Soc. Amer. Bull., vol. 51, p. 513–540.

lately that the merit of this alternative and its attraction as a field subject have begun to be recognized. In the origin of ore, as in the origin of granite, a principal question is—how far did the ingredients travel? According to the way this question is answered, the whole atmosphere for the study of ore genesis will change. One way to attack this question is to look for places from which the ingredients could have come. Ingredients for granite are generally close by; to put it another way, granite if in large quantity lies in or near an environment of silica- and alumina-bearing rocks. Similarly, are not quartz veins mostly close to a source of quartz, as Knopf found them to be in the Mother Lode of California?[8] Are not calcite-bearing veins close to a source of calcite? Or, are some veins close and some distant from possible sources of their gangues? What of potash, which has been the subject of so much debate? To find possible sources of these ingredients, one must look for them in the field. There can, of course, be no substitute for a realistic record of the field occurrence and of the bodies of rocks from which, in the course of recrystallization, these various constituents may have been abstracted. But, more important still, can a nearby source of the ore metal be found?

In his studies in the Sierra Nevada Mayo has often seen black schists in such relation to masses of metamorphic rock on the one hand, and masses of granite on the other, that he strongly suspects a genetic relation between the black schist and the granite. Further, it seems that the black schist is metamorphic rock that has been either enriched in dark constituents such as iron, or depleted of light constituents. Since the nearby granite is rich in light constituents, it is a reasonable supposition that from the granite bodies dark material has been driven out to darken the neighboring schist. The black schist is so heavy as to attract the attention of the prospector, who, in occasional analyses, has found traces of all the metals mined in the Sierra Nevada region. Bodies of such rock aggregating billions of tons have been recognized, but their metal content and the variation of that content are still little

[8] (1929) U. S. Geol. Survey Prof. Paper 157.

known. Here is a definite suggestion of a differentiation of metals developing in the schist, as a part of the metamorphic evolution of which that rock is a part. It can be studied by mapping and by chemical and spectroscopic methods. That serious difficulties would appear is unquestionable, as, for example, in the sampling of the granite and of the black schist. But these difficulties, and the whole subject, can be treated experimentally, in this respect differing from the problems connected with magmatic origin. The magma reservoir, unfortunately, still remains little more than the hieroglyph of an unknown something in the depths of the crust.

After the Sierra Nevada mapping, the following statement was made in the Locke-Billingsley-Mayo paper regarding the ore concentration of that region:

> The Sierra granitoid core is conspicuously poor in ore deposits and its margins are conspicuously rich. Metal would seem to have been taken from the middle, carried to the borders, and fixed there. According to present knowledge, the dark, iron-rich matter liberated by the recrystallization of various rocks low in the metamorphic scale carries various metals. This concept would make a supply of metals for the ore deposit an incident of heat-alteration, and the ore might be deposited at any time in geologic history when motion and heat for the alteration became available. In this light it is interesting to contemplate the great zone of metamorphic rocks stretching from Mexico to Alaska; for it carries an unending succession of granitoid cores with ore deposits grouped around them.
>
> The position of the ore then is not necessarily a question of where the metal came from, for sources would be available over great ranges of structure. It is a question, rather, of the traps which caused the metal to linger and concentrate on its outward journey. These traps are parts of the tectonic pattern. During the evolution of that pattern, both the metal and the motion seem to have been driven out into the adjoining walls. The motion, being continued there, now affects ground already enriched in metal and creates in it local miniatures of the granitic whorls of the core. These whorls have their individual, accompanying heat effects, including concentrations of ore belonging to a second stage. No one knows how many times these processes may have been repeated, how often the metal has been dissolved and reprecipitated, nor to what degree the kind of ore may be controlled by the stage of reconcentration attained.

The question of ore and granite has reached a position where, the more the mapping, the more instances are found of ore bodies that seem to be derived, just as so much of the granite does, from metamorphic rock. Even "cupola" ore is of this kind, for often cupolas have been proved to be drag folds in which, not only the internal structures of the granite, but also the surrounding structures of the wall rocks participate. While not venturing to predict how great a proportion of the ores will prove to have such an origin, the writer is convinced that none of the phenomena usually taken to denote magmatic origin are incompatible with the concept of metamorphic origin.

MENLO PARK, CAL.,
April 1, 1941

DISCUSSION AND COMMUNICATIONS

ALBITE AND GOLD.

The recent paper by David Gallagher in this JOURNAL (Vol. 35, pp. 698–736) is an extremely valuable summary of present knowledge of the genetic relations of gold deposits. The author has presented conflicting opinions with admirable fairness and has performed a signal service in pointing out the lack of precise information upon which conclusions may be based.

The determination of the origin of solutions, the only evidences of which are the effects they have produced, is a matter of the greatest difficulty. A large number of cases are cited where gold deposits lie in or near rocks of albitic character, but propinquity does not necessarily mean consanguinity and it might be added that ore deposits commonly occur in areas where there has been long continued and repeated disturbances and thus in the precise locations where igneous bodies also would be most likely to be injected. Where the mineralogy of the lodes and the character of the wall rock alteration show that the vein solutions were largely sodic, genetic relationship of the deposits to a sodic parent magma must be assumed, but in too many cases ore-bodies have been assigned to certain exposed intrusive rocks on extremely doubtful evidence.

Schwartz[1] has pointed out the diversity of alteration products produced by hydrothermal alteration, and Gallagher finds that even when the study is restricted to gold deposits, "albitization ranges from nil to profound." Schwartz goes still farther and states that in most cases soda is lost, not added. He quotes as examples of this process such deposits as those of Tonopah, Grass Valley and Cripple Creek. Albite can be readily recognized and

[1] Schwartz, G. M.: Hydrothermal alteration of igneous rocks. G. S. A., Bull. 50: 181–237.

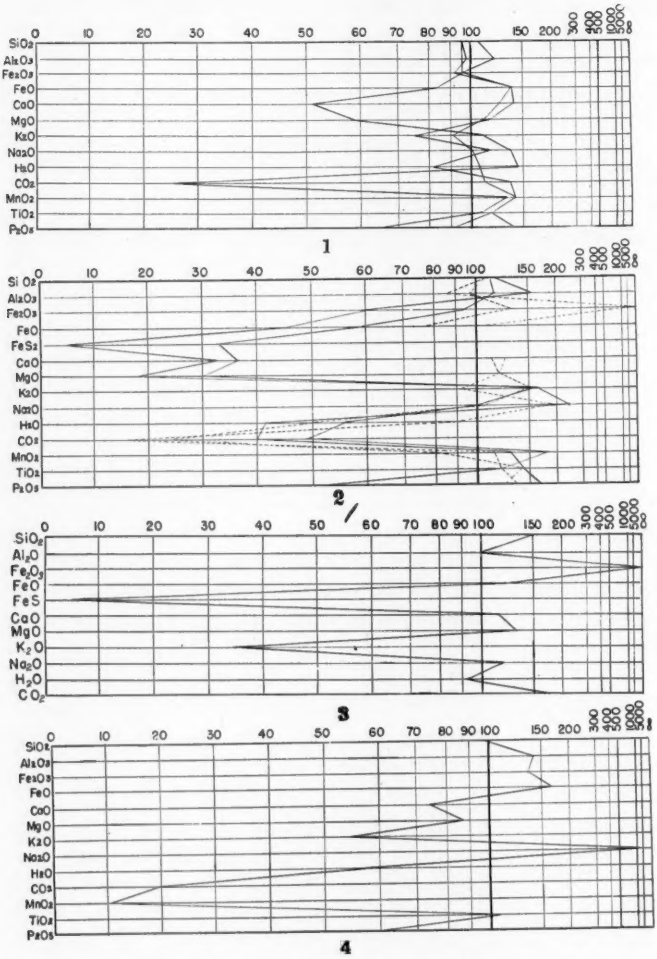

FIG. 1. Straight line diagram showing alteration of porphyry wall rock at Kirkland Lake from analyses in report by E. W. Todd. Ontario Dept. of Mines, Vol. 37, Pt. 2 (1928), pp. 88–89.

FIG. 2. Straight line diagram to show alterations of lamprophyre wall

no doubt as both Schwartz and Gallagher suggest some of the sericite-like minerals in the wall rocks are actually paragonite. However, the matter should be investigated quantitatively and there are comparatively few pairs of analyses upon which to base conclusions. Schwartz has published some of these; a few others are available from reports dealing with gold deposits in the Canadian Shield. These are shown in straight line diagrams (Figs. 1–4). Gains and losses are difficult to determine in wall rock alteration since there is no satisfactory standard for comparison. However, it is evident that if the porphyry at Kirkland Lake has had soda added to it during alteration, potash has been added to a much greater degree (Fig. 1). It seems more likely that soda has actually been lost. This is true of one pair of analyses of syenite and lamprophyre from the same locality but the trend is reversed in the other pair (Fig. 2). At Porcupine there appears to be a great increase of potash as compared with soda (Fig. 3). Until quantitative data are available the presence of some soda-bearing minerals along vein zones cannot be accepted as *ipso facto* proof of the addition of soda. Very likely soda has been added in some cases, but the evidence now available seems to show that in other important deposits potash was added to the wall rocks possibly at the expense of soda originally present in them.

Following the pioneer work of Kemp, Lindgren and others, the igneous source of the solutions from which many ore-bodies were formed came to be accepted by most students of ore deposition. The extension of these ideas to explain, as a genetic relationship, the clustering of ore-bodies around small bodies of intrusive rocks, believed to be the upward projections of larger masses of

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rocks (dotted line) and syenite wall rocks at Kirkland Lake, *op. cit.*, pp. 89–90.

FIG. 3. Straight line diagram to show alteration of wall rocks at Porcupine from report by A. G. Burrows, Ont. Dept. of Mines, Ann. Rept., Vol. 33, Pt. 2 (1924), p. 51.

FIG. 4. Straight line diagram to show alteration of granite wall rocks at the Dikdik Mine, Sturgeon River area. Ont. Dept. of Mines, Ann. Rept., Vol. 45, Pt. 2 (1936), p. 56.

igneous rocks beneath, seemed to be a logical corollary. Hence it came about that it was considered hardly necessary to do more than point out the existence of a neighboring intrusive body of apparently the proper composition, to justify the assigning of an ore-body genetically to that intrusive. The errors thus introduced into geologic literature are too numerous to list.

It was embarrassing enough for geologists to have to admit that many mistakes of this kind have been made, but so far as those working in the Canadian pre-Cambrian were concerned it was still more disconcerting to have important ore-bodies discovered in areas where no suitable intrusives outcrop, and where the conventional theory would indicate little chance of the occurrence of ore. Furthermore, the great depths now reached by mining operations at Porcupine and Kirkland Lake, without any significant change in the type of the ore, seems to be conclusive proof that the source of the ore depositing solutions must still be far below the present workings.

So long as a genetic relationship was assumed between these ores and some rock mass outcropping near by, there was inevitably an uneasy doubt as to the behaviour of the lodes beneath the mine workings. Abandoning the idea of genetic relationship in favour of the hypothesis of localization due to structural control only, obviates some of the difficulties that have faced the student of the older ore deposits at least. The weight of evidence still seems to justify the conclusion that for many ore-bodies, the magma chamber from which the ore-bearing solutions came, lies far below the deepest limits yet reached in mining; and that, in many cases, the veins are the only manifestations of the magma at the present surface.

E. L. BRUCE.

QUEEN'S UNIVERSITY,
KINGSTON, ONT., CAN.,
Nov. 24, 1940.

REVIEWS *

Coal, its Properties, Analysis, Classification, Geology, Extraction, Uses, and Distribution, 2nd Edit. By ELWOOD S. MOORE. Pp. 473. Wiley and Sons, New York, 1940. Price $6.00.

This publication is a welcome revision of the textbook that has been the standard source of information on coal for schools and colleges and for the general public for nearly a generation. The second edition follows closely the satisfactory arrangement of the first, the same chapter headings being used except for a rearrangement of the heading of Chapter XI to read, "The Uses and Preparation of Coal" rather than "The Preparation and Uses of Coal." The book is essentially the same size as the first edition but there has been some change in the space allotted to the different chapters. The greatest change is in Chapter VII, "Fossil Flora of the Coal-forming Periods," which in the first edition required 55 pages but in this edition only 27.

To cover the field of knowledge of coal geology, coal chemistry, coal mining, and coal utilization in a volume of this size is possible only if the author presents various topics discussed in a very condensed form or is very selective in his presentation. Both varieties of treatment are in evidence in the book, so that it might well be called "An introduction to the study of coal" than be given the title assigned to it.

The subject of coal petrography has been given a place in the opening chapter on "The Physical Properties of Coal." The discussion is much condensed and does not reflect the fact that coal literature during the last 20 years has been very largely devoted to this field of interest. The bibliography of coal petrography suffers from too great brevity.

The discussion of fossil plants (Chapter VII) is too largely detached from any application to coal problems. Aside from the fact that the author appears to wish to satisfy the curiosity of the student or reader in regard to the kinds of plants that compose the coal, there seems to be no other purpose in presenting the information in Chapter VII.

In the chapter on "Structural Features of Coal Seams" (Chapter VIII) the brevity of the discussion also seems unreasonable in a book purporting

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, W. S. Bayley, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

to present a discussion of the geology of coal beds. One of the surprising omissions is any reference to the cyclical type of deposition in explanation of some of the structural irregularities mentioned.

In the discussion of the coal fields of the world unfortunate omissions and errors of statement exist. For example, in the discussion of the Illinois and Indiana fields, with which the present writer is most familiar (pp. 395–397), no reference is made to the large quantity of coal mined by open-cut operations. It is stated on page 395 that no shaft deeper than 135 feet is now being operated in Illinois, whereas on page 397 it is stated that "Belleville" coal bed, which should have been called "Herrin" bed, is mined at a depth of 800 feet in the western part of the state (this should have been 725–750 feet in the central and southern part of the state).

The book will undoubtedly continue to occupy an important place among English language textbooks on coal but not the solitary place it has occupied for so long in view of the availability of other books in the English language that have recently appeared, particularly "The Nature and Origin of Coal and Coal Seams," by Raistrick and Marshall, and "The Geology of Coal," by Stutzer and Noé.

GILBERT H. CADY.

Text-book of Geology, Part II, Historical Geology, 4th Edit. By CHARLES SCHUCHERT AND C. O. DUNBAR. Pp. 544; Figs. 343. John Wiley and Sons, New York, 1941. Price, $4.00.

This textbook, which gained renown as Part II of the Text-book of Geology by L. V. Pirsson and Charles Schuchert that appeared in 1915, was revised by Schuchert in 1924, and by Schuchert and Dunbar in 1933. In the present edition the same make-up as previously has been followed but it has largely been rewritten to bring it up to date and many new and excellent illustrations are included. There is recorded here a continuous story of the continuity from the birth of our planet to Recent time, preceded by a prologue of six chapters dealing with basic conceptions of interpretation. Chapter 2, "A Living Record of the Dead" is particularly enlightening and an appendix on "An Introduction to Plants and Animals" is valuable. The book should continue to serve American geology as it has in the past.

Outlines of Structural Geology. By E. SHERBON HILLS. Pages IX and 172; Plates 4; Figs. 105. Cloth, 5 × 7¼. Nordeman Publishing Co., New York. 1940. Price, $2.25.

In his Preface the author states that in this little book he has "aimed at presenting a brief, yet reasonably complete and well-documented summary of structural geology, with special reference to those aspects of the

subject with which the field geologist should be acquainted." He has succeeded well in his aim. Under seven heads he has discussed briefly, but clearly, the subjects of non-diastrophic structures, rock deformation, major crustal structures, folds, faults, structures of igneous rocks, and petrofabric analysis.

The treatment of each subject is necessarily very condensed but in each case the author's definitions and descriptions are so documented by footnotes to the publications of other writers that the reader may follow the discussions as far as he feels it desirable.

For most purposes the author's descriptions are full enough to meet the needs of most students who are not specializing in structural geology. The chapters on major crustal structures, folds and petrofabric analysis are especially noteworthy, because they treat these subjects from the modern point of view and in such a thorough, though simple manner, that they should be welcomed by all beginners in the study of structural geology and by all geologists who wish to review their knowledge of the subject and bring it up to date.

The little book is clearly written, is well illustrated with diagrams, is provided with a good selected bibliography in the way of footnotes, and it contains a fund of information so large as to require nine pages of subject index. It is recommended as a handy little summary of modern views on the principles of structural geology.

W. S. BAYLEY.

Elements of the Petroleum Industry. Edited by E. DEGOLYER. Seeley W. Mudd Fund, Amer. Inst. Min. and Met. Engrs., New York, 1941.

This compendium by twenty well known authors covers the broad field of geology, chemistry, exploration, leasing, trading, royalties, drilling, production, transportation, refining, economics and marketing. Each part is authoritatively and adequately covered. The volume should serve the petroleum industry as its predecessor "Industrial Minerals and Rocks" has so adequately served the mining industry.

BOOKS RECEIVED.

WILLIAM E. BENSON.

Mármores do Muriaé, Estado do Rio de Janeiro. A. B. LAMEGO. Pp. 47; pls. 11; figs. 4; geol. map in color, 16" × 36", scale 1:100,000. Brazil Serv. Geol. e Mineral., Bol. 97. Rio de Janeiro, 1940. *Geology and petrology of the marble belt of Muriaé.*

Alto Rio Brancho. G. C. PAIVA. Pp. 42; pls. 5; figs. 2. Brazil Serv. Geol. e Mineral., Bol. 99. Rio de Janeiro, 1939. *Geology of the Upper Rio Brancho district, situated in extreme north of Brazil. Reconnaissance work on a little known region.*

Estratigrafia do Carvão em Santa Catarina. J. F. DA ROCHA E E. P. SCORZA. Pp. 148; pls. 29; figs. 21; tables 3; maps 1. Brazil Divisão de Geol. e Mineral. Rio de Janeiro, 1940. *Revision of I. C. White's Santa Catarina stratigraphy. A detailed description of the "Gondwana" strata, with emphasis on the coal measures. (Note: change in title from Serviço Geológico e Mineralógico to present form; it is the same organization.)*

Geologia da Costa Nordeste da Baia. J. L. DE MELO, JR. Pp. 11; 1 map, scale 1" = 18 miles. Brazil Div. de Geol. e Mineral., Notas Prelim., N. 20. Rio de Janeiro, 1940.

Geol. Map of Brazil, including parts of neighboring countries. In color; scale, 1 : 7,000,000. Brazil Serv. de Fom. da Prod. Min. Rio de Janeiro, 1938.

Idade do Calcáreo de Calumbi (Sergipe). P. E. DE OLIVEIRA. Pp. 11; pls. 2. Brazil Div. de Geol. e Min., Notas Prelim., N. 19. Rio de Janeiro, 1940. *Chiefly a description of five new fossil species.*

Manganese Deposits at Philipsburg, Granite Co., Mont. E. N. GODDARD. Pp. 47; pls. 9; figs. 5; geol. map 12" × 15", scale 1" = 1,000 ft. U. S. Geol. Surv. Bull 922-G. Washington, 1940. Price, 40 cents. *Well illustrated with cross sections and plans of mine workings.*

Lauderdale County Mineral Resources. V. M. FOSTER AND T. E. MCCUTCHEON. Pp. 238; pls. 1; figs. 23; maps 1. Miss. Geol. Surv., Bull. 41. University, 1940. *Geology of the area and laboratory tests on the clays, sands, and marls.*

Petrology and Genesis of the Third Bradford Sand. P. D. KRYNINE. Pp. 134; figs. 37; tables 23. Penn State Coll. Min. Industries Bull. 29. State Coll., 1940. *Well illustrated with microphotographs.*

Bibliography and Abstracts of Papers on Reservoir Conditions and Mechanics. A. A. P. G., Pacific Coast Section Study Group. Los Angeles, 1940. Price, 50 cents. *Abstracts of 300 titles on 4" × 6½" cards for filing under author, publication, or title.*

Contributions to Virginia Geology. G. W. STOSE, A. I. JONES, R. L. BATES, R. S. EDMUNDSON, L. R. THIESMEYER, D. J. CEDERSTROM, R. O. BLOOMER, B. N. COOPER, AND C. BUTTS. Pp. 185; pls. 26; figs. 21, tables 1. Virginia Geol. Surv., Bull. 51. University, 1939. *Eight short papers on general geology by the above authors.*

El Problema Petrolifero del Peru. A. JOCHAMOWITZ. Pp. 131; pls. 13; tables 12; maps and sections 10. Bol. Cuerpo de Ingenieros de Minas del Peru, No. 125. Lima, 1939. *Covers geological, economic, and political phases of Peruvian oil.*

Tungsten Deposits of Atolia District, San Bernardino and Kern Counties, Cal. D. M. LEMMON AND J. V. N. DORR. Pp. 40; pls. 3; figs. 4; geol. map 20" × 35", scale 1" = 400 ft. U. S. Geol. Surv. Bull. 922-H. Washington, 1940. Price, 25 cents.

Antimony Deposits of a Part of Yellow Pine District, Valley County, Idaho. D. E. WHITE. Pp. 32; pls. 2; figs. 1; geol. map 8" × 18", scale 1" = 800 ft. U. S. Geol. Surv. Bull. 922-I, Prelim. Rept. Washington, 1940. Price, 30 cents.

Antimony Deposits of the Wildrose Canyon Area, Inyo County, Cal. D. E. WHITE. Pp. 18; pls. 2; figs. 2; geol. map 13″ × 19″, scale 1″ = 600 ft. U. S. Geol. Surv. Bull. 922-K. Washington, 1940. Price, 25 cents.

Tin Deposits of the Black Range Catron and Sierra Counties, New Mexico. C. FRIES, JR. Pp. 15; pls. 9; figs. 2; geol. maps 4. U. S. Geol. Surv. Bull. 922-M, Prelim. Rept. Washington, 1940. Price, 50 cents.

Mineral Resources of the Union of South Africa. Pp. 512; figs. 68. S. Africa Dept. Mines. Pretoria. 1940. Price 5s. *The third edition of this excellent publication which covers all the mineral industries of the Union.*

Natural Water Loss in Selected Drainage Basins. G. R. WILLIAMS AND OTHERS. Pp. 59; pls. 2; figs. 5; tables 4. U. S. Geol. Surv. W. S. P. 846. Washington, 1940. Price, 15 cents. *Statistical study of annual water loss from the total rainfall in humid and semi-arid regions east of the Rocky Mts.*

Subsurface Geology and Oil and Gas Resources of Osage County, Oklahoma. L. E. KENNEDY, J. D. MCLURE, H. D. JENKINS, AND N. W. BASS. Pp. 40; tables 5; 1 map, scale 1″ = ½ mile. U. S. Geol. Surv. Bull. 900-D. Washington, 1940. Price, 35 cents. *Part 4, covers area southwest of Bartlesville; Townships 24 and 25 N., Ranges 10 and 11 E.*

Glass Sands and Glass Making Materials in Georgia. Pp. 26; numerous unnumbered tables. Georgia Dept. Nat. Res., Mines Div., Inf. Cir. No. 11. Atlanta, 1940. *A compilation of information from various sources.*

The Flagstone Industry of Georgia. A. S. FURCRON. Pp. 8. Georgia Dept. Nat. Res., Mines Div., Inf. Cir. No. 12. Atlanta, 1940. *Deals with possibility of production of flagstone within the state.*

Porosity, Total Liquid Saturation, and Permeability of Illinois Oil Sands. R. J. PIERSOL, L. E. WORKMAN, AND M. C. WATSON. Pp. 63; figs. 39; tables 53. Ill. Geol. Surv., Rept. Invest. No. 67. Urbana, 1940.

Effect of Fluorspar on Silicate Melts with Special Reference to Mineral Wool. J. S. MACHIN AND J. F. VANECEK. Pp. 10; figs. 6; tables 4. Ill. Geol. Surv. Rept. Invest. No. 68. Urbana, 1940. *Experiments on effect of fluorite on the diameters of rock wool fibres.*

The Clays of West Tennessee. G. I. WHITLATCH. Pp. 355; pls. 10; figs. 16; tables 38; 1 map 28″ × 34″, scale 1″ = 4 miles. Tenn. Div. Geol. Bull. 49. Nashville, 1940.

Malartic Area, Quebec. H. C. GUNNING AND J. W. AMBROSE. Pp. 138; pls. 7; figs. 8; geol. map in color in 4 sheets, scale 1″ = 1500. Canada Geol. Surv. Memoir 222. Ottawa, 1940. Price, 50 cents. *General geology plus detailed description of gold mines.*

SCIENTIFIC NOTES AND NEWS

C. H. BEHRE, JR., William Deering professor of economic geology at Northwestern University, has been appointed professor of economic geology at Columbia to take over the economic geology courses in September.

A portrait of WILLIAM SHIRLEY BAYLEY, painted by J. William Kennedy, was presented to the University of Illinois on June 1 by friends and students of Dr. Bayley.

A. L. DU TOIT, formerly with De Beers and then associated with A. L. Dickinson, has retired from his official duties to 2 Bye Way, Pinelands, Capetown, South Africa where he plans to continue with his researches.

At the Fiftieth Anniversary Celebration of the University of Chicago the geological program will be papers and open discussions for two days, September 25 and 26, on the theme "Frontiers of Knowledge in the Geologic Sciences." The speakers will be R. A. DALY of Harvard on "Continental Terraces and Submarine Valleys"; R. F. FLINT of Yale on "Frontiers of Knowledge in the Field of Glacial Geology"; G. H. CADY of the Illinois Geological Survey on "Frontier Studies of the Physical Constitution of Coal and Their Practical Significance"; R. E. GRIM of the Illinois Geological Survey on "Frontier Researches on the Structure, Properties and Occurrence of Clay Materials and Their Practical Application"; A. I. LEVORSEN, chairman, Research Committee of the A. A. P. G., on "Geological Frontiers in the Search for Oil."

Members of the Society of Economic Geologists are cordially invited. Further details will be announced later or may be obtained from Edson S. Bastin of the University of Chicago.

E. Y. DOUGHERTY, consulting geologist, has moved his headquarters from Toronto to R. 2, Box 600, Bellevue, Washington.

The GROUND WATER DIVISION, Water Resources Branch of the Geological Survey held a meeting of 45 members of the technical staff in Washington, D. C., April 28 to May 3 on administrative and technical problems in the investigation of ground-water resources of the country. Three sessions were devoted to a discussion of the encroachment of salt water upon fresh ground-water supplies, with special reference to the available methods of investigation. With the great demand for water supplies from wells, the problems of salt-water encroachment are becoming increasingly serious, and merit thorough study.

G. M. HALL, head of the department of geology of the University of Tennessee, died in Baltimore, Maryland on April 28.

G. W. BAIN of Amherst University is making an extensive tour of the important mining fields of South Africa.

ALFRED WANDKE, manager of the Guanajuato Consolidated Mining and Milling Co., died in Guanajuato, Mexico on February 18.

R. BRIDGES is president of the Geological Society of South Africa, which awarded its Draper Memorial Medal to S. H. HAUGHTON.